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Fungal Bioremediation: A Sustainable Strategy for Microplastic Removal from Polluted Water

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ABSTRACT

Microplastic (MP) pollution is an escalating global concern, posing serious threats to aquatic ecosystems and human health. These small plastic particles (1µm to 5mm), originating from synthetic products, industrial activities, and the degradation of larger plastic debris, are now ubiquitous in both freshwater and marine environments. MPs enter water bodies through multiple pathways, including wastewater discharge, atmospheric deposition, and agricultural runoff. Once present, MPs can act as vectors for toxic substances such as heavy metals and persistent organic pollutants (POPs), contributing to ecological imbalance, bioaccumulation within food webs, and potential health risks to humans. Addressing this issue requires sustainable and effective remediation strategies. Among emerging solutions, fungi have attracted increasing attention due to their unique biological capabilities. Certain fungal species produce extracellular enzymes—such as laccases and peroxidases—capable of breaking down synthetic polymers. Furthermore, their extensive mycelial networks and biofilm structures provide large surface areas that facilitate the adsorption and physical entrapment of MPs from contaminated waters. Fungal-based bioremediation thus represents a cost-effective, environmentally friendly, and scalable alternative to conventional MP removal methods. This review examines the ecological impacts of MP contamination and explores the potential of fungi as natural allies in mitigating this form of pollution. Advances in fungal biotechnology could play a significant role in integrated water management strategies, supporting cleaner aquatic ecosystems while reducing long-term risks to biodiversity and public health.

INTRODUCTION

Water, covering over 70% of the Earth's surface, is a fundamental resource for all life forms. However, rising pollution levels threaten global water supplies, turning them into repositories of hazardous substances **(Taha *et al.*, 2025)**. Industrial discharge, agricultural runoff, and plastic waste have significantly degraded water quality, endangering aquatic ecosystems and human health. Understanding the sources, consequences, and mitigation strategies for water pollution is essential for safeguarding this vital resource **(Taha *et al.*, 2023b)**.

Industrial activities, agricultural practices, and inadequate waste management are primary drivers of water contamination. Industries such as pulp and paper manufacturing, tanneries, and distilleries discharge toxic chemicals and heavy metals into water bodies, disrupting ecosystems **(Gouda *et al.*, 2023; Taha *et al.*, 2023a)**. In agriculture, excessive use of fertilizers and pesticides, along with improper disposal of animal waste, contributes to nutrient pollution and eutrophication. In many developing countries, untreated wastewater used for irrigation exacerbates contamination. Oil spills and improper waste disposal further degrade water quality, making pollution a critical environmental concern **(Chowdhary *et al.*, 2020)**.

Plastic pollution, a global environmental crisis, has historical roots dating back to the Mesoamerican use of natural rubber around 1600 BC. Today, rivers transport nearly 80% of plastic waste into aquatic environments, where freshwater systems act as both conduits and reservoirs for macroplastics—plastic items larger than 5mm. Common pollutants such as plastic bags, bottles, and fishing gear accumulate in sediments, disrupting ecosystems. Increasing public awareness has driven policy reforms, industrial initiatives, and environmental advocacy aimed at reducing plastic waste **(Chia *et al.*, 2021)**.

Microplastics (MPs), defined as plastic particles between 1.0µm and 5mm, have emerged as a significant environmental concern due to their persistence and potential toxicity. MPs originate from the breakdown of larger plastics or are intentionally manufactured for use in consumer products such as cosmetics, toothpaste, and industrial cleaners. Scientific classifications of MPs vary, underscoring the need for standardized definitions **(Bhatt *et al.*, 2023)**.

Recent research indicates growing concern over MP pollution, particularly as smaller particles pose greater ecological risks. Alongside MPs, mesoplastics (5– 25mm) and nanoplastics (< 1µm) exhibit distinct behaviors and contribute to contamination. These plastic fragments act as carriers for toxic substances, including heavy metals and persistent organic pollutants (POPs), further threatening biodiversity and ecosystem stability **(Horton & Barnes, 2020)**. According to the National Oceanic and Atmospheric Administration (NOAA), MPs are the most prevalent form of marine debris. Although their full physicochemical impacts remain under investigation, their widespread distribution raises concerns over long-term ecological consequences. Pollution from human activities, compounded by climate change, is increasingly affecting even the most remote ecosystems and diverse species **(Ustaoğlu *et al.*, 2020)**.

For MP degradation, traditional physical and chemical treatments can be applied; however, recent attention has turned to biodegradation as an environmentally sustainable alternative. This approach aligns with the United Nations' 2030 Agenda for Sustainable Development Goals (SDG) 6 (Clean Water and Sanitation) and 14 (Life Below Water). In biodegradation, microorganisms such as bacteria, fungi, and algae produce enzymes capable of breaking down plastic polymers into smaller units. These fragments can then be mineralized or assimilated, making biodegradation a promising strategy to combat plastic pollution **(Nasrabadi *et al.*, 2023)**.

1. Classification of MPs

MPs are typically classified based on their physical form and chemical composition. Structurally, they appear in various morphologies, including fibers, microbeads, fragments, and films. Chemically, MPs are composed of different polymers, characterized by their degradation potential and toxicity. The most prevalent types of polymers found in MPs include polypropylene (PP), polystyrene (PS), polyethylene (PE), polyurethane (PU), polyvinyl chloride (PVC), and polyethylene terephthalate (PET). Additives such as flame retardants and stabilizers are often incorporated during plastic manufacturing to enhance specific material properties **(Sadri & Thompson, 2014)**.

1.1. Classification based on physical form

-Fibers are among the most abundant forms of MPs detected in sediments and marine organisms. Wastewater treatment plants (WWTPs) are typically ineffective at completely removing synthetic fibers, such as those made from polyester and nylon. Consequently, these microfibers are discharged with effluents into natural water bodies, including rivers, lakes, and oceans and even enter terrestrial ecosystems **(Llorca *et al*., 2022)**.

-Plastic debris primarily enters marine environments from land-based sources *via* wind or river transport. According to **Sucharitakul *et al*. (2021)**, a global visual survey of ocean surfaces identified that approximately 20% of visible plastic debris originated from fishing-related activities, 58% from non-fishing sources, and 22% were of mixed origin. Among non-fishing sources, about 10% were plastic films or bags, and 18% were foamed PS and plastic bottles. Notably, fishing-related materials accounted for nearly 70% of the total plastic debris by weight, representing the most significant contributor in terms of mass.

-Microbeads are spherical plastic particles incorporated into cosmetics, household cleaning agents, and industrial abrasive products. In the United Kingdom, emissions of microbeads from facial exfoliants alone are estimated to range from 16 to 86 tons annually. These particles are washed down household drains, partially removed by WWTPs, and eventually released into aquatic ecosystems **(Lamprini *et al*., 2021)**.

1.2. Classification based on chemical composition

MPs also differ significantly in their chemical composition, which influences their environmental persistence and degradation behavior. Common polymer types include:

-Polyethylene (PE), a hydrocarbon polymer made from ethylene monomers (C_2H_4) *via* polymerization, forming linear or branched chains, as shown in Fig. (1a). It is highly hydrophobic, limiting microbial interaction. PE exists in several forms, notably low-density PE (LDPE) and high-density PE (HDPE). HDPE is more solvent-resistant due to its compact structure and high intermolecular forces, while LDPE's branched configuration grants it resistance to acids, alcohols, and alkalis **(Bardaji & Moretto, 2020)**.

-Polystyrene (PS) is synthesized through polymerization of styrene monomers derived from ethylene and benzene *via* catalytic dehydrogenation (Fig. 1b). It demonstrates high thermal stability (up to 200°C) but is environmentally problematic due to the release of toxic monomers and additives into ecosystems. Micro- and nanoplastic fragments of PS can accumulate in aquatic environments, with chronic exposure levels exceeding 300ppm classified as hazardous by the U.S. Environmental Protection Agency **(Du & Cia, 2020)**.

-Polypropylene (PP) is a versatile polymer existing in amorphous, semicrystalline, and crystalline forms (Fig. 1c). The commercially available type is typically a mixture of 75% semicrystalline and 25% amorphous structures. Its widespread use in food packaging and molded products stems from its impermeability to water vapor, oils, and fats, which also hinders biodegradation **(Verbeek & Rajamaki, 2020)**.

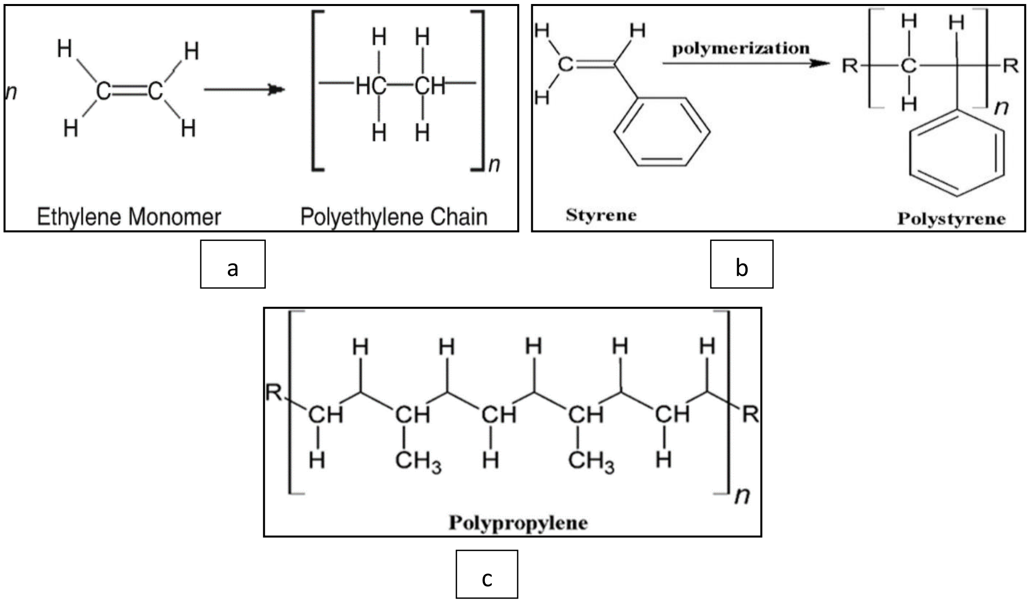

Fig.1. Chemical structures of common polymers: (a) Polyethylene; (b) Polystyrene; and (c) Polypropylene **(Bhatt *et al.*, 2023)**

2. Sources of MP pollution

MPs originate either from primary production as small particles or from the degradation of larger plastic materials, as depicted in Fig. (2).

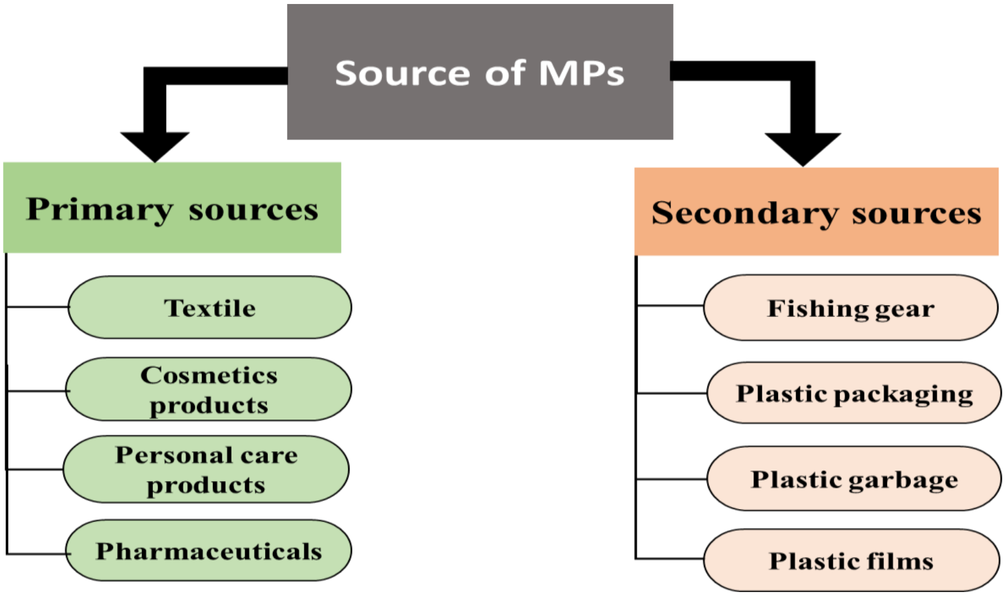

Fig. 2. Various sources of microplastic pollution

2.1. Primary sources

Primary MPs are intentionally manufactured to be less than 5mm in size for use in specific industrial and consumer products. These include materials used to enhance texture, durability, or product performance **(Llorca *et al.*, 2022)**. Major primary sources are summarized in Table (1).

Table 1. Primary sources of microplastics

Source	Chemical Composition	Reference
Textile industry	Polyester	**Deng (2020)**
Cosmetic products (e.g., shower gels, facial cleansers)	Polyethylene	**Habib (2020)**
Industrial sources	Polyethylene, nylon, polypropylene	**Hou *et al.* (2021)**
Marine coatings and shipping	Surlyn, acrylic, polyetherimide, polyphenylene sulfide, ethylene vinyl alcohol, acrylonitrile, nylon, polyisoprene, PVC, PU	**He (2022)**
Personal care products / sewage sludge	Polystyrene, polyester, amino thermoset plastic, polyallyl diglycol carbonate	**Huang (2021)**
Urban sewage	Polyethylene, polystyrene, polypropylene	**Habib (2020)**
Industrial zones	Polyester, nylon	**Wang (2020)**
Tertiary industries	Polyethylene	**Brandon (2020)**
Sludge and WWTPs	Polypropylene, acrylic, nylon, rubber	**Deng (2020)**

2.2. Secondary sources

Secondary MPs are formed through the fragmentation of larger plastic items under physical, chemical, and biological influences **(Chia *et al.*, 2021)**. Common secondary sources are listed in Table (2).

Table 2. Secondary sources of microplastics

Source	Chemical Composition	Reference
Disposable plastic tableware	Polypropylene (PP), polystyrene (PS), polyethylene (PE)	**Andrady (2017)**
Plastic packaging (e.g., bags, bottles)	Oriented Polypropylene (OPP), Cast Polypropylene (CPP), PP, PE, Polyvinyl Alcohol (PVA), Ethylene-Vinyl Acetate (PVA), Polybutylene Succinate (PBS), Polycaprolactone (PCL)	**Alomar (2016)**
Fishing nets and ropes	PE, Low-Density Polyethylene (LDPE), PA (nylon), PP	**Yang (2023)**
Fishery and domestic sewage	Polyvinyl Chloride (PVC), PE, Polyamide (PA)	**Zhang *et al.* (2020)**
Industrial activity	PE, PP, nylon	**Sharma (2022)**
Agricultural films	PE, LDPE	**Alomar (2016)**

3. Impact of MPs on human and aquatic organisms

MPs have emerged as pervasive pollutants infiltrating aquatic ecosystems, terrestrial environments, and even the atmosphere, posing significant risks to both human and ecological health, as illustrated in Fig. (3).

Human exposure to MPs primarily occurs *via* three main pathways: ingestion through contaminated food and water, inhalation of airborne particles, and dermal contact **(Kwon *et al*., 2020)**. Once inside the body, ingested or inhaled MP particles are subjected to physiological defense mechanisms such as phagocytosis, mucociliary clearance, and lymphatic transport **(Prata, 2019)**. Despite these defenses, some particles persist and accumulate in the respiratory or gastrointestinal systems, triggering the release of pro-inflammatory cytokines, proteolytic enzymes, and reactive oxygen species (ROS). These responses may result in chronic inflammation, oxidative stress, and associated health issues such as fat deposition, hormonal imbalances, respiratory complications, intestinal obstruction, and general loss of vitality. Moreover, MP exposure has been linked to reproductive toxicity, including hormonal dysregulation and infertility.

Aquatic organisms, particularly filter-feeding invertebrates such as mollusks, zooplankton, and ascidians, are especially vulnerable to MP contamination. These organisms can accumulate MPs along with other pollutants like heavy metals and pesticides, leading to bioaccumulation and biomagnification throughout the food chain. Physical impacts of MP ingestion in aquatic fauna include gastrointestinal blockages, impaired nutrient absorption, respiratory distress, and, in severe cases, strangulation. Additionally, sub-lethal effects such as skeletal deformities, epidermal damage, reduced motility, altered reproductive capacity, and behavioral disturbances have been widely reported **(Sucharitakul *et al*., 2021)**.

MPs also exert deleterious effects on aquatic flora, particularly phytoplankton and microalgae, which form the base of the aquatic food web. These primary producers can adsorb MPs onto their surfaces, resulting in decreased photosynthetic efficiency and reduced cellular viability. MP adhesion disrupts energy and nutrient uptake, thereby inhibiting algal growth and biomass production. Prolonged exposure may also lead to structural damage to algal cell walls due to particle aggregation and sedimentation, ultimately destabilizing aquatic food webs and ecosystem functions **(Barboza *et al*., 2020)**.

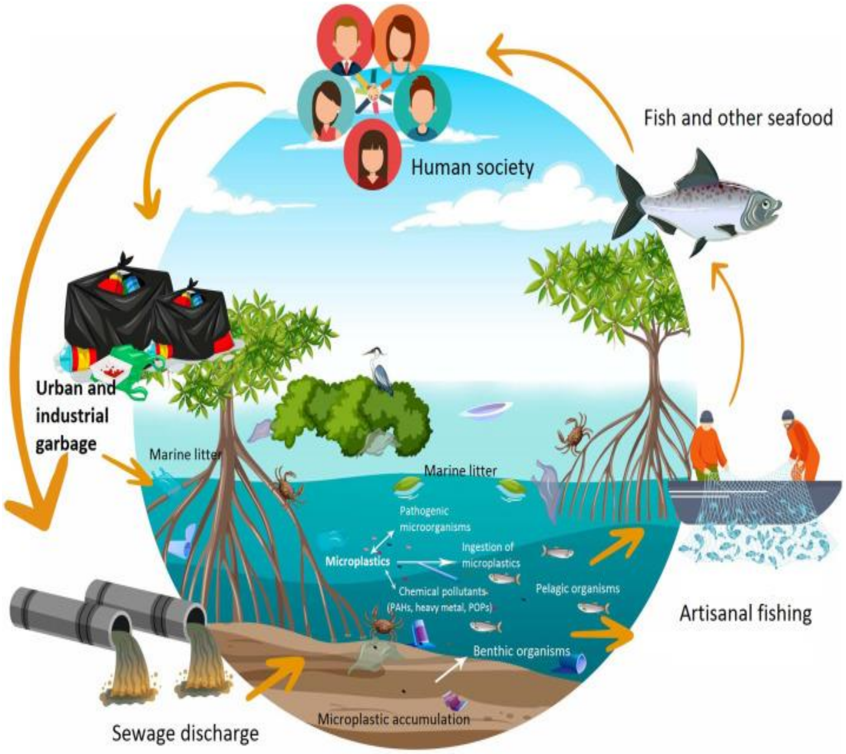

Fig. 3. Microplastic impacts on humans and aquatic organisms **(Garcés-Ordóñez *et al*., 2022)**

4. Remediation methods of MPs

4.1. Traditional methods

The degradation of plastics in the environment is a protracted process influenced by several environmental factors, such as temperature, solar radiation, humidity, and the physicochemical characteristics of the polymers, pH, and biological activity (**Padervand *et al.*, 2020)**. Various mechanisms have been identified as contributing to the breakdown of plastic materials:

4.1.1. Thermal degradation

Thermal degradation involves the decomposition of large and complex plastic polymers into simpler and smaller molecular fragments under elevated temperatures. When oxygen is present, this process is referred to as thermal oxidation. Exposure to visible light (400– 760nm) can initiate degradation, while infrared radiation enhances thermal oxidation, resulting in notable changes in the material's malleability and surface characteristics **(Hou *et al.*, 2021)**.

4.1.2. Photodegradation

Photodegradation occurs when high-energy photons impact polymer chains, breaking them into smaller fragments. This process is accelerated by the absorption of solar radiation and the presence of oxygen, leading to photooxidation. It is particularly prevalent in plastics exposed to extended periods of sunlight, contributing to their surface embrittlement and fragmentation **(Chamas *et al.*, 2020)**.

4.1.3. Ozone-induced degradation

Ozone, a potent oxidant, contributes significantly to MP degradation in both aquatic and atmospheric environments. Upon exposure to ozone and ultraviolet light, oxidative reactions occur on the plastic surface, leading to chain scission and the formation of functional groups such as carbonyls and hydroxyls. These changes promote material brittleness, surface cracking, and eventual fragmentation into nanoplastics. PS is especially vulnerable to this oxidative degradation. Ozone-induced ageing is currently being investigated as a potentially sustainable strategy to accelerate the decomposition of persistent plastic pollutants **(Kim *et al.*, 2022)**.

4.1.4. Mechanochemical degradation

Mechanochemical degradation results from the application of mechanical forces, such as ultrasonic waves or abrasion, that physically break down plastic polymers. This process is often enhanced by thermal or electrical stimuli. In natural environments, MPs are subject to abrasion by materials such as wood fragments, shells, and other debris, gradually forming rounded particles similar in morphology to naturally weathered sediments **(Enfrin *et al.*, 2020)**.

4.2. Biological degradation

Biological degradation represents an environmentally sustainable approach to MP remediation, leveraging the metabolic activities of microorganisms such as bacteria, fungi, and algae. Among these, fungal species have demonstrated notable efficiency in MP breakdown, a process known as mycodegradation **(Natesan *et al.*, 2021)**.

4.2.1. Algal degradation

Algae play a significant role in the biodegradation of MPs, especially in wastewater environments. Algal species can adhere to plastic surfaces, initiating degradation through the secretion of exopolysaccharides and ligninolytic enzymes. These enzymes interact with the polymer matrix, facilitating its breakdown. Some algae have demonstrated the ability to utilize plastics as a carbon source, as evidenced by elevated protein and carbohydrate content in species colonizing PE surfaces. Mechanistically, algal degradation involves processes such as surface fouling, corrosion, hydrolysis, leaching component breakdown, and pigment-induced diffusion **(Taniguchi *et al*., 2019)**.

In addition to degrading plastic polymers, algae have been shown to break down plastic-associated toxicants such as bisphenol A (BPA). For instance, *Chlorella vulgaris* effectively degraded BPA to undetectable levels within 168 hours, without residual estrogenic activity. Similarly, *Chlorella fusca var. vacuolata* converted BPA into non-toxic metabolites **(Moog *et al*., 2019)**.

4.2.2. Bacterial degradation

Bacterial degradation of MPs is primarily mediated through enzymatic hydrolysis, where secreted enzymes bind to the plastic surface and cleave the polymer chains into smaller units—monomers, dimers, and oligomers—that are assimilated as carbon sources. Bacteria possess metabolic flexibility, enabling them to synthesize necessary enzymes under nutrient-limiting or energetically favorable conditions **(Ustaoğlu *et al*., 2020)**.

The degradation may proceed *via* aerobic or anaerobic pathways. In aerobic environments, oxygen acts as the terminal electron acceptor, producing carbon dioxide, water, and biomass. In contrast, anaerobic degradation employs alternate electron acceptors such as nitrates or sulfates, leading to the formation of methane and other reduced products. Both processes play vital roles in mitigating plastic pollution and enhancing the sustainability of waste management practices **(Babaahmadi *et al*., 2024)**, as illustrated in Fig. (4).

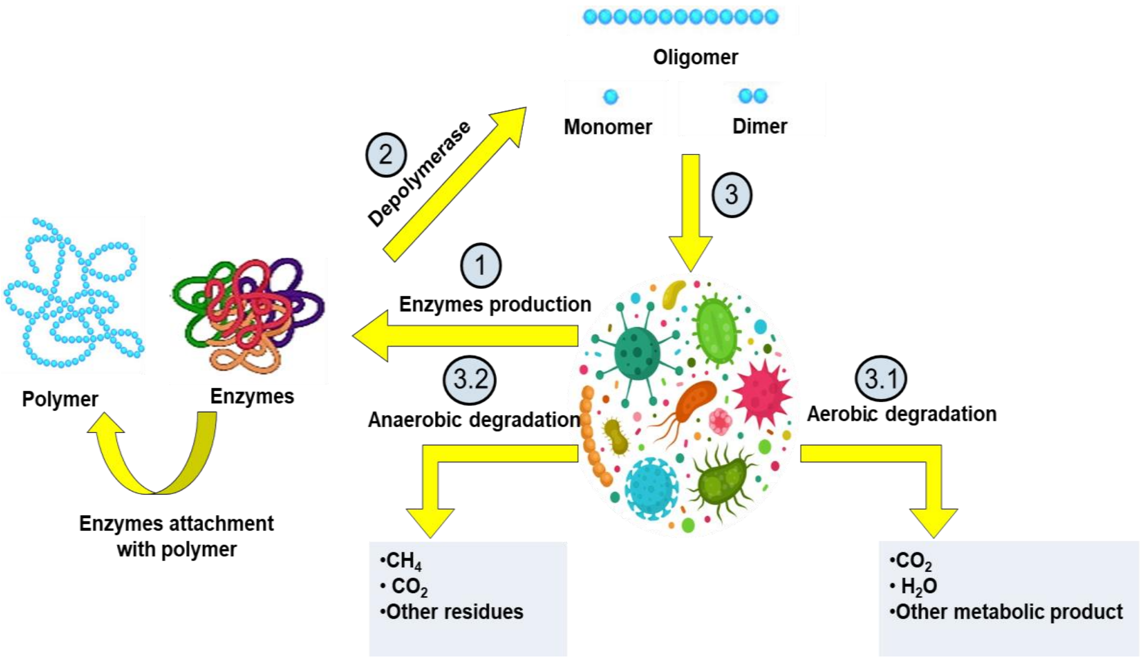

Fig. 4. Aerobic and anaerobic biodegradation

4.2.3. Fungi

Fungi possess diverse metabolic capabilities and are known to synthesize a variety of extracellular multienzyme complexes and secondary metabolites, making them prime candidates for investigating MP biodegradation potential. These organisms can reduce the hydrophobicity of plastic surfaces by introducing functional groups such as carbonyl, carboxyl, and ester groups, thereby enhancing polymer degradability. The effectiveness of fungal-mediated plastic degradation can be assessed through biomass growth, structural changes in the polymer, and biochemical analyses such as biochemical oxygen demand (BOD), enzymatic assays, and monitoring of degradation byproducts, including CO_2 evolution. Various fungal genera, including *Aspergillus*, *Penicillium*, *Mucor*, and *Trichoderma*, have been widely reported for their MP-degrading capabilities **(Lee & Ten, 2021; Gouda *et al.*, 2024)**.

5. Fungi-mediated bioremediation

Fungi have evolved unique mechanisms for bioremediation, largely attributed to their production of enzymes such as proteases, amylases, and lipases. These enzymes facilitate the utilization of complex substrates like proteins, starches, and lipids, even under extreme environmental conditions, including acidic or alkaline environments **(Taha & Gouda, 2025)**. Many fungal species can metabolize cellulose, hemicellulose, and pectin as carbon sources. Their role as primary decomposers of recalcitrant natural polymers—such as lignin, keratin, and chitin—demonstrates their capacity for breaking down complex substrates resistant to microbial degradation **(Krause *et al.*, 2020)**.

5.1. Advantages of fungal bioremediation

Fungi offer several advantages over bacteria in the bioremediation of MPs, primarily due to their distinct biological and ecological traits. Their filamentous hyphal structures enable strong adherence to MP surfaces and penetration into the material's interior. This invasive ability facilitates the formation of functional chemical groups, such as carboxyl, carbonyl, and ester bonds on the polymer surface, effectively reducing hydrophobicity and enhancing degradation **(Ren *et al*., 2021)**.

5.2. Significant fungal strains involved in bioremediation

Numerous filamentous and unicellular fungal strains have demonstrated the ability to degrade plastic polymers and utilize them as carbon sources. Table (3) summarizes key fungal strains reported for MP biodegradation, including their sources, plastic types, and observed degradation outcomes.

Table 3. Representative fungal strains involved in the biodegradation of microplastics

Fungal Strain	Source of Isolation	Type of Plastic	Key Observations	Reference
Aspergillus terreus and *Aspergillus sydowii*	Rhizosphere soil of *Avicennia marina*	Polyethylene (PE)	Notable weight loss and reduced tensile strength; morphological and chemical changes after 60 days of incubation	**Gao *et al.* (2022)**
Aspergillus flavus and *Candida tropicalis*	Marine coastal soil contaminated with plastic waste	High-density PE (HDPE), Low-density PE (LDPE)	Structural and morphological alterations; biofilm development observed after 30 days	**Zahari *et al.* (2021)**
Aspergillus fumigatus	Agricultural soil	Polybutylene succinate adipate (PBSA)	Fungal colonization, plastic weight loss, and secretion of lipolytic enzymes	**Chien *et al.* (2022)**
Cladosporium cladosporioides	Agricultural soil	Polylactic acid (PLA), Polybutylene succinate (PBS), Polycaprolactone (PCL)	Clear zone formation indicating enzymatic activity on agar plates	**Penkhrue *et al.* (2015)**
Purpureocillium lilacinum	Landfill soil	Low-density PE (LDPE)	Biofilm formation is	**Spina *et al.* (2021)**

			accompanied by morphological alterations and CO_2 release	
Cladosporium herbarum and *Fusarium solani*	Laboratory culture	Polyurethane (PU) foam	Significant morphological and structural degradation was observed after 70 days	**Ren *et al.* (2021)**

6. Fungal pathways involved in MP bioremediation

Fungi contribute to MP degradation through a sequential process involving surface attachment, enzymatic action, assimilation, and mineralization. Initially, fungal hyphae adhere to MP surfaces, enabling colonization. Fungi then secrete extracellular enzymes such as laccases, peroxidases, and esterases, which oxidize and depolymerize the plastics. These modifications render the MPs more accessible for further breakdown and assimilation. Ultimately, these polymers are mineralized into CO_2, water, and biomass (Fig. 5). Moreover, certain fungi produce biosurfactants that increase the solubility of hydrophobic plastics, enhancing degradation efficiency **(Ganesh *et al.*, 2020)**.

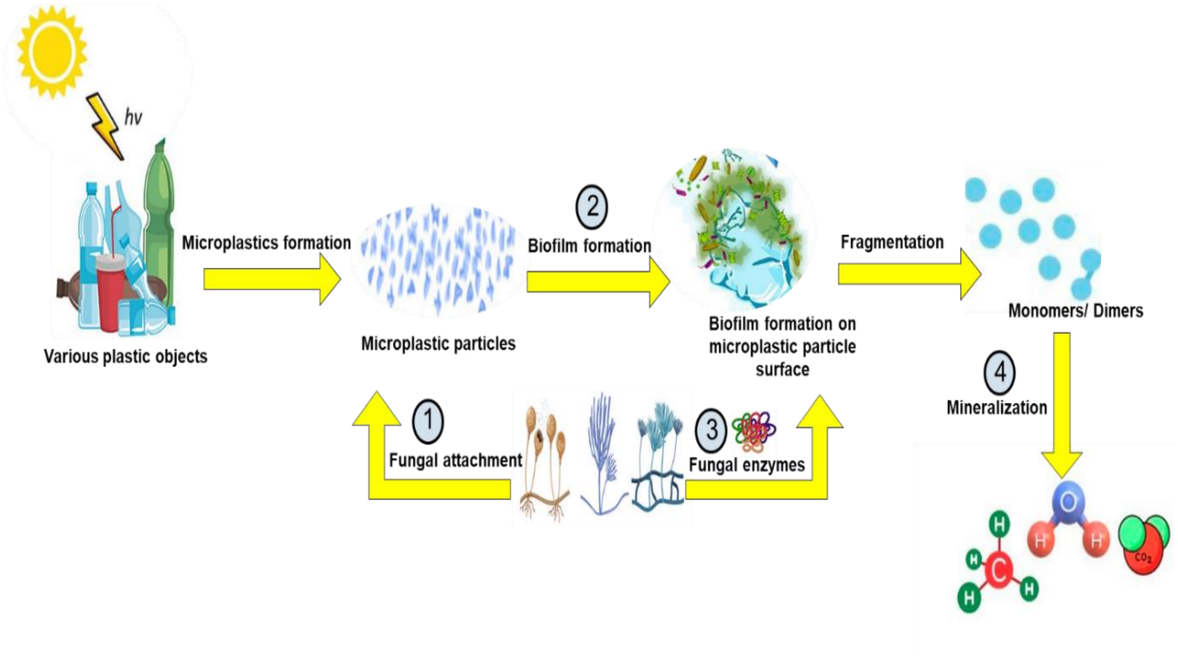

Fig. 5. General pathway of fungal in bioremediation of microplastics

6.1. Initial attachment via hydrophobin

Fungal attachment to plastic surfaces represents a critical initial step in the biodegradation process. This adhesion is mediated by hydrophobins, surface-active proteins secreted by filamentous fungi. Hydrophobins facilitate fungal adaptation to various environments by forming hydrophobic aerial structures and promoting hyphal attachment to hydrophobic substrates, thereby enhancing microbial colonization **(Santacruz-Juárez *et al*., 2021)**.

6.2. Colonization and biofilm formation

Biofilm development is essential for fungal-mediated plastic degradation. Biofilms consist of fungal cells embedded in an extracellular matrix, which anchors them to the plastic surface. Surface properties such as hydrophobicity, roughness, and thermal properties influence microbial community establishment during colonization. The presence of mineral oils may also facilitate biofilm formation by enhancing hydrophobic interactions between fungi and plastic polymers like PE. The biofilm formation process includes spore deposition, germination, hyphal branching, network formation, colony expansion, and spore release **(Atanasova *et al*., 2021; Tamoor *et al*., 2021)**.

6.3. Degradation via extracellular enzymes

Fungi produce diverse extracellular and membrane-bound enzymes, predominantly hydrolases and oxidases, capable of cleaving plastic polymers **(Ren *et al*., 2021)**. These enzymes, detailed in Table (4), degrade polymers such as PLA, PU, PBS, and others through specific biochemical reactions, facilitating plastic breakdown.

Table 4. Enzymes associated with fungal-mediated microplastic degradation

Fungal Strain	Enzyme(s)	Target Plastic Polymer(s)	Reference
Pestalotiopsis microspore	Serine hydrolase	Polyester-based polyurethane (PU)	**Sivan (2011)**
Fusarium solani	Cutinase	Polybutylene succinate (PBS)	**Hu *et al.* (2016)**
Candida rugose and *Rhizopus delemar*	Lipase	Polybutylene adipate-co-terephthalate (PBAT), Polylactic acid (PLA), Polybutylene terephthalate (PBT)	**Kaushal *et al.* (2021)**
Tritirachium album	Proteinase K	Polylactic acid (PLA), Polybutylene succinate (PBS)	**Kaushal *et al.* (2021)**
Penicillium griseofulvum and *Xepiculopsis graminea*	Esterase	PU	**Magnin *et al*. (2019)**

Phanerochaete chrysosporium (white-rot fungus)	Manganese peroxidase, Lignin peroxidase, Laccase	Polyvinyl chloride (PVC), Nylon	**Paszczynski and Crawford (1995)**
Trametes versicolor and *Pleurotus ostreatus*	Laccase	Polyethylene (PE)	**Sivan (2011)**
Aspergillus fumigatus	Dehydrogenase, Oxidase, PHB depolymerase	Polyhydroxybutyrate (PHB)	**Montazer *et al.* (2019)**

6.4. Final mineralization of plastics

The terminal stage of MP degradation involves the assimilation and complete oxidation of breakdown products. Functional groups such as hydroxyl, carboxyl, carbonyl, sulfhydryl, and phosphate are essential for this process. Cytochrome P450 monooxygenases play a pivotal role in hydroxylating alkanes and polyaromatic hydrocarbons, leading to β-oxidation and eventual mineralization into CO_2 and biomass. Remarkably, the energy yield from PE oxidation (−422 to −425 kJ/mol O_2) is comparable to that from glucose (−479 kJ/mol O_2), highlighting its potential as a microbial carbon and energy source **(Asiandu *et al.*, 2021)**.

7. Environmental factors influencing mycodegradation of MPs

Several environmental parameters significantly affect the efficiency of fungal-mediated MP degradation, including the plastic's chemical composition, ambient pH, temperature, and humidity levels **(Alekseyeva *et al*., 2022)**.

7.1. Plastic type and chemical composition

Biodegradation rates vary with polymer structure and crystallinity. Biodegradable plastics like polylactic acid (PLA) and polybutylene succinate (PBS) contain ester linkages that are susceptible to enzymatic hydrolysis. In contrast, conventional plastics such as PET, high-density PE (HDPE), and PVC possess highly crystalline, hydrophobic backbones that hinder microbial access and enzymatic attack. Additionally, additives such as stabilizers and plasticizers may influence degradation rates, either promoting or inhibiting enzymatic action depending on their chemical nature **(Yu *et al*., 2022)**.

7.2. pH

The ambient pH profoundly influences fungal metabolism and enzyme activity. Most plastic-degrading fungi, such as *Aspergillus* and *Penicillium*, exhibit optimal enzyme production and activity in slightly acidic to neutral conditions (pH 5–7). Deviations from this range may impair fungal growth and reduce the efficiency of biodegradation **(Zhang *et al*., 2020)**.

7.3. Temperature

Temperature significantly impacts fungal growth, enzyme production, and the physicochemical properties of plastics. Optimal degradation typically occurs in mesophilic conditions (25– 35°C). While moderate increases in temperature enhance metabolic activity and degradation rates, extreme temperatures (above 40°C) may denature fungal enzymes, whereas low temperatures can suppress fungal activity and slow down plastic breakdown **(Alekseyeva *et al*., 2022)**.

7.4. Humidity

Humidity is essential for fungal colonization and enzyme secretion. High humidity facilitates fungal adhesion to plastic surfaces and supports hyphal growth. In contrast, dry conditions reduce enzyme productivity and hinder plastic degradation. Moist environments may also promote polymer swelling or oxidation, increasing susceptibility to microbial attack **(Zhang *et al*., 2020)**.

CONCLUSION AND FUTURE PERSPECTIVES

MP contamination has emerged as a significant threat to aquatic ecosystems due to increasing plastic production, long environmental persistence, and potential health risks. Current remediation strategies remain limited in effectiveness. Fungal-based bioremediation, or mycoremediation, represents an environmentally friendly, sustainable alternative. Comparative studies suggest that fungi may outperform bacteria in MP degradation due to their enzymatic diversity and substrate adaptability. Future research should focus on isolating and characterizing novel fungal strains with enhanced plastic-degrading capabilities, as well as developing robust microbial consortia for efficient biodegradation. Advancing our understanding of fungal metabolic pathways and optimizing environmental conditions will be critical in realizing the full potential of fungal-mediated MP remediation.

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