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Unseen allies-Fungi as natural solutions for a cleaner environment

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Abstract: Fungi have many different roles in keeping the environment healthy. These roles aren't often recognized, but they make fungi key to fixing today's ecological problems. This review focuses on what fungi can do for environmental monitoring, bioremediation and ecological restoration work. Fungi have a remarkable metabolic versatility and ecological adaptability, which allows them to degrade complex organic contaminants and heavy metals, pharmaceutical waste, and even plastic. Symbiotic and mycorrhizal fungi are helpful for phytoremediation and soil regeneration. We use fungi for biomonitoring tools, fungal biosensors, and hybrid technologies. These technologies pair fungal systems with things like biochar adsorption and AI monitoring. They show even more clearly how fungi help with sustainable environmental care. Fungi have a remarkable ability to solve ecological problems. Their potential is huge, but people mostly ignore them. The reasons include limited molecular reference information, confusion about how to classify them, and problems with public acceptance. These issues are considerable barriers to using them on a large scale. Therefore, we can fix these problems by collecting more fungal species, building DNA reference libraries, and combining different technologies. Environmental chemists, taxonomists, and microbial environmentalists should work together across various fields. This will open up new ways to restore ecosystems and reduce pollution. Above all, seeing fungi as ecological partners we can't do without is crucial. It helps make new and creative, easy to use on a large scale, flexible, and long-lasting solutions for a cleaner planet.

Key words: Bioremediation; Environmental monitoring; Fungal biosensors; Fungi; Plastic degradation

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1. Introduction

Fungi are key to bioremediation, with mycoremediation using their ability to break down many environmental pollutants [1]. As saprotrophic organisms, they recycle key nutrients —carbon, nitrogen, phosphorus—by breaking down organic material [2,3]. Symbiotic fungi, like arbuscular mycorrhizae, aid in restoring land. They promote plant growth and enhance soil quality [4]. They even help remove toxins. Such toxins are heavy metals, pesticides, and plastics—done through absorption, transformation, or degradation [5]. These roles make fungi truly critical. They support nutrient cycling, habitat recovery, and pollution control [6].

Fungi offer an incredible diversity of traits that make them valuable partners in reducing environmental pollution. However, fungi remain largely overlooked in practical remediation efforts. This is mainly due to challenges such as difficulties in accurate species identification, insufficient genomic and functional data, and a scarcity of real-world examples. Furthermore, societal and regulatory barriers are rarely explored in depth, which continues to delay the integration of fungi into mainstream environmental management practices. Consequently, the potential of fungal-based approaches have not been fully underutilized in large-scale ecological recovery efforts.

This review gives a current look. It covers how we use fungi in pollution management, ecosystem monitoring, plant-based remediation, and habitat restoration. In addition, it pulls together new scientific work. It shows growing role of fungi in helping to repair damaged environments, and points out next steps to strengthen their part in sustainable remediation.

2. Fungi in Environmental Monitoring and Bioremediation

Biodegradation of Organic Pollutants

Numerous fungal species have been studied. They use particular enzyme systems to degrade various organic contaminants. Table 1 provides a comparison view. It covers key fungal groups, linked pollutant types, how well they break down pollutants, and main enzymes in these processes. This summary highlights two points. Fungi in biodegradation fit particular pollution management approaches and have a wide range of functional variations.

Mycoremediation of Heavy Metals

Numerous kinds of fungi are highly effective at eliminating met-

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Table 1. Representative fungal species involved in the biodegradation of major organic pollutants, with degradation efficiencies and pathways.

Fungal species	Target pollutant (s)	Degradation efficiency/conditions	Key enzymes/pathways	Reference
Phanerochaete chrysosporium	Phenanthrene, pyrene, PAHs, crude oil hydrocarbons	80–95% removal of phenanthrene (50 mg L^{-1}) within 10–14 days under aerobic shaking conditions	Lignin peroxidase, manganese peroxidase, laccases	[7, 9]
Trametes versicolor	Synthetic textile dyes (e.g. Reactive Blue 19), PAHs	85–100% decolorization of dyes within 5–10 days; 70–90% degradation of low-molecular-weight PAHs within 2 weeks	Laccases, peroxidases	[7, 8, 10]
Aspergillus niger	Diesel, crude oil, pesticides	60–80% degradation of total petroleum hydrocarbons (TPH) within 15 days in contaminated soils; efficient degradation of pesticides	Cutinases, oxidoreductases	[9]
Pleurotus ostreatus	Synthetic dyes, phenolic compounds	80–95% decolorization of dyes (e.g. Congo Red) within 7–14 days	Laccases, versatile peroxidases	[7, 8]
Aspergillus tubingensis	Polyethylene, polyurethane (plastic waste)	30–58% weight loss or surface erosion of polyethylene films over 4–6 weeks under laboratory conditions	Cutinases, oxidative enzymes	[10, 11]
Pestalotiopsis microspora	Polyester polyurethane (plastic waste)	Up to 43% reduction in polymer mass within 6 weeks under microaerophilic conditions	Urethanase, esterase	[11]

als. They accomplish this by bioaccumulation and biosorption. Table 2 gives details on typical fungal groups. It includes target metals, removal efficiencies, and mechanisms. These figures show clearly great promise. Fungi act as useful bio-tools for cleaning up heavy metals in contaminated soils and wastewater.

Mycofiltration

Mycofiltration is a nature-based remediation method. It captures and degrades contaminants in soil and water by using the filtration abilities of fungal mycelium, particularly species from genera such as *Pleurotus* and *Stropharia*[16]. These fungal networks work well at capturing a range of contaminants. They include microbial pathogens, suspended solids, agricultural chemical runoff, and petroleum-based compounds. This contributes to and maintains the health of ecosystems [17]. Results from field trials and small-scale applications have been positive. *Stropharia rugosoannulata* was put in drainage channels and buffer zones. Nutrient and sediment levels fell 60–90%. Additionally, fecal bacteria also went down a lot [17]. Similarly, *Pleurotus* species were added to filtration beds. These beds handle agricultural runoff. They capture excess nitrogen effectively and break down pesticide residues before they reach aquatic systems [18]. However, there are certain issues with the wider use of mycofiltration systems. These issues combine ecological and technical concerns. Maintaining a constant water flow through the fungus substrate is one issue. Another is preventing obstructions caused by accumulated debris. We also need to consider seasonal variations in fungus activity. Making sound plans is necessary to long-term maintain of system functionality as well [18]. Overcoming these issues is crucial to transforming mycofiltration into a reliable, long-term solution for environmental cleanup and repair.

Volatile Organic Compound (VOC) Removal

Fungal genera such as *Beauveria* and *Cladosporium* have shown significant potential for capturing and metabolizing volatile organic compounds (VOCs). This ability has been observed in two circumstances. One is controlled indoor environments, the other is industrial exhaust systems [19,20]. These fungi can adjust to different surroundings. That's why they are excellent choices for bio-based air treatment. They offer a green, low-cost option, which is better than conventional filtration technologies [21,22]. *Cladosporium* and *Beauveria* are used in demonstration-scale systems. They treat air streams contaminated with aromatic compounds like toluene and xylene. These systems remove 70% to 95% of the pollutants [19,22]. These biofilters take advantage of the resilience of fungal biofilms. The biofilms can remain active even when humidity and pollution change. This means steady performance with little upkeep. Although we've made progress, there are still issues with operating them. For long-term, practical use, three elements are essential. Maintain proper moisture levels, manage fluctuating VOC loads, and prevent obstructions caused by excessive biofilm buildup. Therefore, we need more research and better engineering to make fungal VOC biofiltration technologies more scalable and stable in real-world industrial conditions.

Biomonitoring Indicators

Species of fungi can play a crucial role in various ecosystems as bioindicators of measuring the levels of pollution. For example, changes in the mycorrhizal population may indicate shifts

Table 2. Representative fungal species involved in heavy metal remediation, with removal efficiencies and biosorption capacities.

Fungal species	Target heavy metal	Removal efficiency/biosorption capacity	Mechanism	Reference
Aspergillus niger	Pb^{2+}	75–96% removal at 100 mg L^{-1} within 3–5 days; biosorption capacity 50–80 mg g^{-1}	Biosorption, bioaccumulation	[12, 15]
Trichoderma harzianum	Cd^{2+}	65–85% removal; biosorption 40–60 mg g^{-1} biomass	Biosorption	[13, 15]
Penicillium chrysogenum	Hg^{2+}	70–90% removal within 5 days in liquid medium	Biosorption, transformation	[12, 14]
Aspergillus flavus	As^{3+}	~60% uptake; accumulation up to 25 mg g^{-1} biomass	Bioaccumulation, detoxification	[14, 15]
Rhizopus arrhizus	Cu^{2+}	85–98% removal in 48 h; biosorption 90 mg g^{-1} biomass	Rapid biosorption	[12, 15]

in land health, reflecting disruptions to these unique ecosystems [23]. In addition, a reduction in fungal fruit bodies in an ecosystem can point to issues such as acidification or heavy metal contamination [24]. Furthermore, lichenized fungi may serve as reliable indicators of air pollution, due to their sensitivity to changes in the quality of the respective environment [25]. These fungi can accumulate pollutants such as sulfur dioxide, nitrogen oxides, and heavy metals, making them effective tools for atmospheric monitoring [26]. Therefore, these biological indicators provide evidence of the significance of fungi in the monitoring of ecological balance and their health, as well as the identification of pollution sources.

Fungal Biosensors

Fungal biosensors function by using the natural reactions of fungal cells or their enzymes to detect certain environmental pollutants. When these biological elements come into contact with substances like heavy metals, phenolic compounds, or changes in pH, they trigger biochemical reactions that produce measurable signals. This signal is then converted into a measurable output, which could be optical, colorimetric, or electrochemical in nature [27,28]. Combining these fungal sensing components with suitable transducers allows for precise, real-time detection of pollutants, even in complex environmental settings (Figure 1).

Target pollutants are detected by fungal bioreceptors like cells, enzymes, or mycelium networks. The interaction between the analyte and the fungal component generates a measurable signal (e.g., colorimetric, fluorescent, or electrochemical), which is then converted and quantified by a transducer and readout system. This setup allows for sensitive and specific detection of a broad range of environmental contaminants across diverse conditions.

Fungal biosensors have some unique advantages over bacterial systems. In applications involving environmental monitoring and remediation, these are particularly evident. Naturally, fungi can withstand a broad pH range. They handle scarce nutrients and chemical stress too. This ability helps them stay stable when used out in the field. Fungi have thread-like hyphae. These hyphae provide a large surface area, which helps them contact more pollutants. This makes them really effective in complex settings such as soil and wastewater [29,30]. Bacterial biosensors often rely on engineered genetic circuits for specificity. Fungi, though, reach similar sensitivity via diverse, naturally occurring biochemical pathways. Their extracellular enzyme systems are a key strength. They make fungi ideal for detecting hydrophobic pollutants —like phenolics and aromatic hydrocarbons [27-32]. Additionally, structure of fungi and their physiology let them work well in immobilized or solid-state sensors. This makes real-world environmental monitoring more feasible [28,33].

Fungal biosensors have real-world examples. One is engineered *Aspergillus nidulans*—it has fluorescent markers to spot arsenic. Another is *Saccharomyces cerevisiae*; its systems are designed to detect endocrine disruptors or environmental oxidative stress [31]. In addition, some fungi naturally react to pollutants. *Pleurotus ostreatus* and *Trametes versicolor* are such kinds. They're used to detect phenolic compounds and synthetic dyes [32].

Mycoremediation of Plastic Waste

Fungi break down synthetic plastics mainly with extracellular enzymes. These enzymes start the depolymerization process. *Aspergillus tubingensis* and *Trichospora microspora* secrete cutinases, esterase and ureanase. These enzymes specifically target ester bonds and urethane linkages in polyurethane and other polyester-based plastics; this makes the polymer matrix break down [34,35]. Cutinases and esterase focus on polyester bonds in materials such as polyethylene terephthalate (PET). Ureanase specifically breaks urethane bonds—they help break down polymers together [36-38]. Additionally, oxidative enzymes like laccase and peroxidase generate reactive radicals. These radicals further attack and modify the aromatic parts of plastic molecules [36-38]. These enzyme reaction pathways work together, effectively shortening polymer chains, reducing molecular weight, and creating conditions that allow fungi to absorb and transform them later.

Plastic degradation efficiency depends on both polymer type and fungal strain. Under laboratory conditions, polyurethane usually degrades faster than polyethylene or polystyrene. Typical degradation rates, time periods and byproducts are listed in Table 3. The main metabolic products

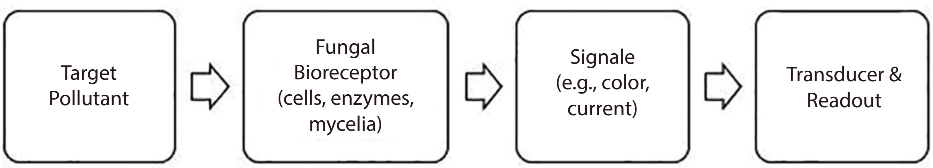

Fig. 1. Schematic representation of the working principle of fungal biosensors

Table 3. Representative fungal species, enzyme systems, degradation timeframes, and byproducts associated with plastic waste mycoremediation

Plastic type	Representative fungal species	Key enzymes involved	Typical degradation timeframe	Main degradation byproducts	References
Polyurethane (PU)	*Aspergillus tubingensis*, *Pestalotiopsis microspora*	Cutinases, urethanases, esterases, laccases	4–8 weeks (30–60% weight loss)	Short-chain oligomers, CO_2, H_2O, biomass	[34–38]
Polyethylene (PE)	*Aspergillus niger*, *Penicillium simplicissimum*	Cutinases, laccases, peroxidases	6–12 weeks (20–60% surface degradation)	Oxidized fragments, CO_2, H_2O, biomass	[36–38]
Polystyrene (PS)	*Aspergillus* spp., *Fusarium* spp.	Oxidative enzymes (peroxidases, laccases), esterases	Several weeks to months (slow)	Monomers, oxidized oligomers, CO_2, biomass	[37,38]

from fungal plastic degradation are oligomers, carbon dioxide, water and fungal biomass. This shows the process achieves partial mineralization at least, and almost no harmful secondary residues are produced.

Biotransformation of Pharmaceuticals and Hormones

More people are becoming aware capacity of fungi to alter hormones and pharmaceuticals. It's an effective way to cut down environmental contamination. Fungal species have many different enzymatic systems, which can transform and break down many kinds of pharmaceutical residues. These include antibiotics, pain relievers, and endocrine-disrupting hormones —all common in wastewater from treatment plants [39]. Some key species stand out here. *Trametes versicolor, Phanerochaete chrysosporium, Aspergillus niger*, and *Mucor hiemalis* can all break down hard-to-remove contaminants. Examples are diclofenac, carbamazepine, naproxen, and 17β-estradiol [40]. Certain enzymes are used by fungi to make these modifications. The primary ones include cytochrome P450 monooxygenases, laccases, and other types of peroxidases. These enzymes speed up oxidative reactions, changing the chemical structures of these tiny pollutants [41]. Through these mechanisms, fungi help reduce the toxicity of contaminated water. This improves the overall quality of treated wastewater. Their work also reduces the harm caused by leftover pharmaceuticals. This helps keep aquatic environments healthier [42]. We need to learn more about how fungi break down these substances and their metabolic processes. This is key for creating better, more sustainable bioremediation technologies.

Table 4 gives details on typical fungal biotransformation processes. It includes the enzymes involved and the degradation products that result.

Soil Detoxification and Regeneration

Soil detoxification and regeneration are important processes that depend a lot on fungal activity. The fungi play an important role in restoring microbial balance within the soil, which is necessary to maintain healthy ecosystems [43]. Species such as *Trichoderma harzianum*, *Aspergillus terreus*, *Penicillium chrysogenum*, and *Pleurotus ostreatus* are widely recognized for their ability to degrade pesticides, herbicides, and other agrochemical remains [44,45]. White-rot fungal species such as *Phanerochaete chrysosporium* and *Trametes versicolor* are useful in breaking down organic pollutants and heavy metals through enzymatic actions and biosorption in the post-industrial land [46]. These fungal species detoxify the soil habitats, making it safer and more favourable for the growth of plants by degrading and changing toxic compounds. In addition, their mycelial networks improve the soil structure and porosity by increasing the cycling of nutrients, promoting soil fertility [47]. This natural process promotes a more vibrant and durable agricultural landscape. Promoting fungal activity in the soil ecosystem can lead to considerable help in rejuvenating degraded land and ensuring its long-term productivity for future generations [48].

Integration with Phytoremediation

Phytoremediation is a process that involves plants to eliminate, transfer, stabilise or destroy contaminants in the soil and water. This can be significantly improved through the integration of mycorrhizal fungi. These fungi form symbiotic relationships with plant root systems and thereby improve the absorption of essential water and nutrients [49]. Arbuscular mycorrhizal fungal species such as *Glomus intraradices*, *Rhizophagus irregularis*, and *Funneliformis mosseae* are reported to improve tolerance of plants to heavy metals such as cadmium, lead and arsenic [21,50]. Ectomycorrhizal fungi such as *Pisolithus tinctorius* and *Laccaria bicolour* have also demonstrated strong potential to help trees and bushes in contaminated soils [51,52]. This mutualist interaction not only increases the tolerance of plants to several toxic elements and organic pollutants, but also increases their general growth and resistance under stress [53]. Research has shown that the incorporation of mycorrhizal fungi in phytoremediation strategies can lead to more effective remediation results by improving the bioavailability of nutrients and increasing the area of the root surface, allowing a greater absorption of pollutants. Ultimately, the synergistic effects of plant-fungal associations have a promising approach to address environmental pollution and the restoration of contaminated ecosystems.

3. Outlook and Future Directions

To move fungal bioremediation to a larger scale, several key research challenges must first be addressed. Improving our understanding of global fungal diversity is crucial, along with clarifying taxonomic uncertainties and expanding molecular reference data. These steps are essential to identify ecologically and functionally important fungi, many of which are still unknown or appear only as 'dark taxa' revealed by environmental DNA studies. Improving these core areas will make it possible to design more focused and efficient remediation strategies by identifying fungal groups best suited for breaking down pollutants [54–57].

Fungal bioremediation has demonstrated great potential as a sustainable method for tackling complex environmental pollutants [12]. However, to unlock the full potential of fungal bioremediation, future studies should combine fungal systems with other technologies to make them more efficient, scalable, and practical for real-world conditions [46,47]. Promising approaches include integrating fungal degradation processes with biochar-based adsorption, constructed wetlands, and membrane bioreactor systems to enhance pollutant removal

Table 4. Representative pharmaceuticals and hormones biotransformed by fungi, associated enzymes, and main transformation products.

Compound	Fungal species/enzymes	Main metabolites or transformation products	References
Diclofenac	*Trametes versicolor*; laccases, peroxidases	4′-Hydroxydiclofenac, quinone imines, conjugated metabolites	[40, 42]
Carbamazepine	*Phanerochaete chrysosporium*; laccases	10,11-Epoxycarbamazepine, hydroxylated metabolites	[39]
Ibuprofen	*Aspergillus niger*, *Penicillium chrysogenum*	Hydroxylated and demethylated derivatives	[41]
Sulfamethoxazole	*Trametes versicolor*; peroxidases	Hydroxylated and nitro-derivatives	[39, 40]
Estradiol/Ethinylestradiol	*Trametes versicolor*, *Pleurotus ostreatus*; laccases	Quinones, hydroxylated estrogens, conjugated metabolites	[39]

from industrial and municipal waste streams [36,39]. Similarly, integrating fungal enzymes with nanomaterials could allow for more precise pollutant breakdown, and combining fungal monitoring with AI-powered remote sensing could improve early detection and control of contaminated areas [46]. These combined approaches can make treatment processes more efficiency while expanding the scope of fungal applications in environmental remediation.

Technology isn't the only factor. Social and regulatory issues will be key to getting fungal bioremediation into wide use. Many countries have rules for releasing and using fungi. This includes genetically modified strains —these rules are often incomplete, fragmented, or not enforced evenly [51,52]. People are concerned about their safety as well. These include the potential for horizontal gene transfer and effects on organisms that are not the intended target. They show we need clear risk assessments and standardized safety rules [51]. It can also be difficult for the public to accept. Fungi are mostly viewed as pathogens or organisms that cause spoilage. Clear communication, input from stakeholders, and practical demonstration projects are key here. They'll help gain public trust and get more people using fungi to make the environment cleaner [51].

We need to tackle these technical, regulatory, and social challenges. This is vital to turn fungal bioremediation from promising laboratory research into practical, deployable environmental solutions.

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Declaration of Competing Interest

Sajeewa S. N. Maharachchikumbura is an Editorial Board Member of [Environmental Chemistry and Safety] and was not involved in the editorial review or the decision to publish this article.The author declares that there is no conflict of interest regarding the publication of this paper.

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