Fungal Bioremediation: An Effective and Alternative Eco-Friendly Tool for Environment Clean-Up

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DOI: https://doi.org/10.5281/zenodo.17312633

Accepted on: 28/09/2025, Published on: 10/10/2025

Abstract:

Soil-inhabiting fungi around plant roots play a vital role in improving soil fertility and plant health by degrading organic pollutants such as petroleum hydrocarbons, aromatic amines, and azo dyes, along with detoxifying heavy metals like cadmium, chromium, zinc, copper, and nickel. The mechanisms of fungal bioremediation involve adsorption, bioaccumulation, bio volatilization via enzymatic degradation processes (esterification, hydroxylation, deoxygenation, dehydrogenation, methylation etc.) and phytobial remediation. Fungi possess significant capabilities in degrading complex organic compounds by producing extracellular ligninolytic enzymes like laccase, xylanases, manganese peroxidase, lignin peroxidase, cytochrome P450 monooxygenases etc. Arbuscular Mycorrhizal Fungi (AMF), in association with Plant Growth-Promoting Rhizobacteria (PGPR), enhance pollutant degradation and plant growth, forming an efficient phytobial remediation system. Additionally, white-rot fungi (Pleurotus ostreatus, P. tuber-regium) and Trichoderma species effectively degrade recalcitrant pollutants. Fungal bioremediation, also termed mycoremediation, has emerged as an innovative and sustainable strategy for environmental restoration. However, research on commercial application of fungi as a natural bioremediator is still limited. This review focuses on the future potential of fungi and their symbiotic interactions as cost-effective, eco-friendly strategies to promote sustainable agriculture and pollution management.

Keywords: *Fungal bioremediation, AMF, PGPR, White-rot fungi, Trichoderma, Sustainable agriculture.*

Introduction:

According to the Environmental Protection Agency (EPA), USA Bio-remediation is a "treatment that uses naturally occurring organisms to break down hazardous substances into less-toxic or non-toxic substances" (Hlihor 2017). Anthropogenic pressures from industrialization and urbanization have led to accumulation of recalcitrant pollutants such as polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and heavy metals (Akcil et al., 2015). Conventional remediation techniques like chemical oxidation, soil excavation, and thermal treatment are often costly, energy intensive, and prone to generating secondary wastes, limiting their sustainability for large-scale agricultural application (Prasad, 2017). Microorganisms (e.g., fungi and bacteria), green plants or combinations of all these can be used together to convert toxic pollutants into carbon dioxide (CO2), water (H2O), microbial biomass, inorganic salts and other products which are less toxic to environment as well as to human beings,

Fungi are central to many bioremediation strategies (microembolisation) because of their ecological ubiquity, metabolic versatility, and unique biochemical toolkits. Soil-inhabiting fungi associated with plant rhizospheres perform multiple ecosystem functions: decomposing organic matter, cycling nutrients, improving soil structure, and mediating pollutant transformation and immobilization (Gadd, 2004; Singh, 2006). Fungi have multiple mechanisms that enable the breakdown or immobilization of pollutants, including adsorption, bioaccumulation, enzymatic oxidation, and biomineralization. Adsorption and biosorption occur via functional groups on the chitin- and glucan-rich fungal cell wall, enabling rapid initial binding of metal ions and hydrophobic organics. Bioaccumulation and intracellular sequestration then allow further transformation, while bio volatilization—observed for select elements such as selenium and mercury—can transform contaminants into volatile, less toxic species (Li, Liu, & Gadd, 2020).

Among these mechanisms, extracellular enzymatic degradation is particularly significant. White-rot and other ligninolytic fungi secrete a suite of oxidative enzymes that catalyse nonspecific, radical-based oxidation of recalcitrant aromatics (Durairaj et al., 2015; Purnomo, Putra, & Kondo, 2014). Complementary intracellular systems, cytochrome P450 monooxygenases, enable hydroxylation, dealkylation, dichlorination, and other transformations that increase pollutant hydrophilicity and biodegradability (Durairaj et al., 2015). These combined extracellular–intracellular pathways underlie fungal capacity to degrade PAHs, chlorinated pesticides (e.g., heptachlor, atrazine), azo dyes, and other persistent organic pollutants (Nwachukwu & Osuji, 2007; Purnomo et al., 2014).

Further, fungus is responsible for decomposing leaf litter. In fact, fungi are the only organisms on Earth that can decompose wood (Rhodes 2013). Decomposition of starches, hemicelluloses, celluloses, pectins and other sugar polymers can be done by Aspergillus and other moulds. Some species of aspergilla also have the ability to degrade fats, oils, chitin and keratin. These species also perform bio deterioration, the process of degradation of human origin substances like paper and textiles (cotton, jute, linen etc.) (Rhodes, 2013).

White-rot fungi (e.g., *Pleurotus ostreatus*, *Phanerochaete chrysosporium*, *Trametes versicolor*) are exceptional lignin degraders and effective at mineralizing structurally complex xenobiotics, including PAHs, PCBs, dioxins, and textile dyes (Singh, 2006; Deshmukh, Khardenavis, & Purohit, 2016).

Trichoderma spp. (e.g., *T. viride*, *T. harzianum*) combine fast growth, enzyme production (laccases, peroxidases), and rhizosphere competence, making them valuable for simultaneous pollutant degradation and plant growth promotion (Divya, Prasanth, & Sadasivan, 2013).

Aspergillus and Penicillium species contribute to biodegradation of simpler organics and exhibit notable biosorption of heavy metals (Gazem & Nazareth, 2013). Additionally, many marine-derived fungi tolerate saline or metal-rich conditions and have been used to treat industrial effluents (Ceci et al., 2019).

Fungal cell walls, rich in chitin, glucans, and melanin, play a pivotal role in biosorption and bioaccumulation of heavy metals. Many fungi also secrete organic acids and siderophores that aid in metal chelation and immobilization, thereby reducing bioavailability and toxicity (Barrech et al., 2018). This dual capability—degrading organic pollutants and sequestering inorganic contaminants—positions fungi as versatile agents in complex pollution scenarios

Soil co-contamination with hydrocarbons and metals (e.g., at petroleum sites) presents particular challenges because metals can inhibit microbial degraders, alter redox chemistry, and reduce pollutant bioavailability through sorption to hydrophobic soil fractions (Kuyukina, Krivoruchko, & Ivshina, 2018; Lai et al., 2009). Nevertheless, fungi display adaptive strategies—biomineralization, chelation, vacuolar sequestration—that enable persistence and remediation under combined stressors. For example, ureolytic fungi such as *Neurospora crassa* can precipitate metal carbonates that immobilize metals while providing localized niches for hydrocarbon degradation (Li et al., 2017a; Li et al., 2019).

Fungal Species Utilized in Bioremediation:

Fungal species belonging to hyphomycetes, ascomycetes and basidiomycetes groups which shows distinct physiological traits, enzymatic profiles, and ecological niches that influence their pollutant degradation capacity. Among them White-rot fungi, Trichoderma spp., Aspergillus spp., Penicillium spp., and Arbuscular Mycorrhizal Fungi (AMF) are most extensively studied genera.

White-Rot Fungi (WRF) - A decomposer of the polymer lignin:

White-rot fungi (WRF) belong to basidiomycetes with their unique ability to degrade lignin, a polymer in plant cell walls. Their ability to secrete lignin-modifying enzymes (LMEs) that oxidize recalcitrant organic compounds (e.g., peroxidases, laccases) (LMEs: peroxidases, laccases) robust ligninolytic enzyme system, also allows them to degrade structurally similar xenobiotic pollutants such as polycyclic aromatic hydrocarbons (PAHs), chlorophenols, pesticides, and synthetic dyes (Singh, 2006). Unlike most bacteria or brown-rot fungi, WRF contains nonspecific oxidative enzyme systems also which act on multiple pollutant types.

Species such as *Pleurotus ostreatus*, *Pleurotus tuber-regium*, *Phanerochaete chrysosporium*, *Trametes versicolor*, *Lentinula edodes*, *Bjerkandera adusta*, and *Irpex lacteus* have been widely documented for their pollutant degradation efficiency. *P. chrysosporium* produces high levels of lignin peroxidase (LiP) and manganese peroxidase (MnP), allow disruption of nonphenolic aromatics and halogenated hydrocarbons (Purnomo et al., 2014). *T. versicolor* and *L. edodes* used for dye decolorization in textile effluents, achieving over 80% color reduction through laccase-mediated oxidation (Jebapriya & Gnanadoss, 2013).

Moreover enzymatic oxidation, WRF generate hydrogen peroxide (H_2O_2)-producing oxidases that drive peroxidase reactions, forming reactive radicals capable of attacking complex pollutant structures. Their oxidative metabolism also produces low-molecular-weight mediators (e.g., veratryl alcohol, oxalate) that expand substrate range and enhance redox cycling. For instance, *Pleurotus* species can degrade heptachlor (94%), atrazine (78%), and aldrin (90%) under optimized soil conditions (Nwachukwu & Osuji, 2007; Xiao et al., 2011).

Advantages of White-Rot Fungi over Bacteria

1. **Broad substrate specificity:** Capable of degrading multiple organic pollutants concurrently.

2. **Extracellular enzyme system:** Acts outside the cell, minimizing substrate transport limitations.
3. **Tolerance to high pollutant concentrations:** Can survive in harsh environments unsuitable for bacteria.
4. **No need for pollutant pre-conditioning:** Enzymatic oxidation is largely non-specific and radical-based.
5. **Wide environmental adaptability:** Effective across diverse temperature, pH, and salinity ranges.

Due to the benefits mentioned above, white rot fungi known for its role as universal decomposers and can also be looked into as biofilters, solid-state bioreactors and soil amendment systems for organic pollutant degradation.

- **Trichoderma spp. - Dual Role as Bioremediatory and Biofertilizer:**

The genus *Trichoderma* (Ascomycota), a saprophytic fungus commonly found in soil and decaying organic matter. They play a role of bio remediators and biofertilizers due to their enzymatic versatility and plant-growth-promoting effects.

Trichoderma harzianum and *T. viride* produce oxidative enzymes such as laccases, MnP, and versatile peroxidases which facilitate degradation of phenolic compounds, pesticides, and polyaromatic hydrocarbons (PAHs) even under saline or metal-stressed conditions (Divya, Prasanth, & Sadasivan, 2013).). Apart from pollutant degradation, *Trichoderma* species improve soil health by enhancing nutrient availability and suppressing plant pathogens through mycoparasitism and antibiosis. They also promote root elongation and biomass accumulation. It supports both soil detoxification and crop productivity.

- **Fusarium and Related Fungi - Hydrocarbon and Aromatic Amine Degradation**:

Fusarium solani, *Hypocrea lixii*, and other Fusarium species have been isolated from hydrocarbon-polluted soils and shows degradation capacity for polycyclic aromatic hydrocarbons (PAHs) such as pyrene and phenanthrene (Hong, Park, & Gadd, 2010). These fungi also tolerate and transform toxic metals like Cu and Zn, often forming metal complexes or precipitates on their hyphal surfaces. Fusarium strains also degrade aromatic amines (AAs)—pollutants derived from dyes, herbicides, and industrial effluents. Such as *Podospora anserina* detoxifies 3, 4-dichloroaniline (3,4-DCA) through arylamine N-acetyltransferase (NAT2) activity, producing less toxic acetylated derivatives (Martins et al., 2009). This enzymatic pathway plays a vital role in the biotransformation of herbicide breakdown products such as diuron and linuron, preventing their carcinogenic and mutagenic impacts.

Arbuscular Mycorrhizal Fungi (AMF) - Symbiotic Partners in Phytobial Remediation:

Arbuscular Mycorrhizal Fungi (AMF) shows mutualistic symbiosis with the roots of over 80% of terrestrial plant species and play a crucial role in nutrient cycling, soil aggregation, and stress tolerance. AMF species such as *Glomus intraradices*, *Rhizophagus irregularis*, and *Acaulospora laevis* extend hyphal networks deep into the soil matrix, increasing the effective surface area for nutrient absorption and pollutant uptake. These fungi reduce metal bioavailability through chelation, adsorption onto hyphae, and glomalin production. Glomalin-related soil proteins not only bind heavy metals but also improve soil aggregation and stability (Zhang et al., 2019).

When AMF operate in concert with plant growth-promoting rhizobacteria (PGPR), they form phytobial consortia that enhance pollutant degradation rates. PGPR release biosurfactants and siderophores that mobilize pollutants, while AMF assist in translocation and detoxification processes. This synergy significantly boosts remediation efficiency in agricultural soils contaminated with both organic and inorganic pollutants (Banitz et al., 2013).

It helps in repairing bad soil, removing toxic substances from the soil, improving water quality and promoting root development of plants so AMF is a main component for sustainable agro-ecological restoration.

Comparison of Major Fungal Groups

Fungal Group	**Representative Species**	**Major Pollutants Degraded/Immobilized**	**Primary Mechanism**	**Notable References**
White-rot fungi	*Pleurotus ostreatus*, *Phanerochaete chrysosporium*, *Trametes versicolor*	PAHs, dyes, pesticides, PCBs	Ligninolytic enzymes (LiP, MnP, laccase)	Singh (2006); Purnomo et al. (2014)
Trichoderma spp.	*T. harzianum*, *T. viride*	Phenols, PCP, hydrocarbons	Laccase-mediated	Divya et al. (2013);

			oxidation, dehalogenation	Vacondio et al. (2015)
Aspergillus spp.	*A. niger*, *A. terreus*	Metals, hydrocarbons, pesticides	Biosorption, hydroxylation, deoxygenation	Gazem & Nazareth (2013); Deng et al. (2015)
Penicillium spp.	*P. chrysogenum*, *P. digitatum*	Metals, industrial effluents	Biosorption, enzymatic degradation	Rhodes (2013)
Fusarium spp.	*F. solani*, *Hypocrea lixii*	PAHs, aromatic amines, metals	Oxidation, acetylation, sequestration	Hong et al. (2010); Martins et al. (2009)
AMF	*Glomus intraradices*, *Rhizophagus irregularis*	Metals, hydrocarbons	Chelation, glomalin-mediated immobilization	Morel et al. (2013); Zhang et al. (2019)

Fungal Bioremediation in Co-Contaminated and Marine Environments:

Many industrial regions contaminated with organic pollutants and heavy metals, creating complex environments. Soils near petroleum extraction, metal smelting, and waste-disposal sites frequently contain mixtures of hydrocarbons, PAHs, phenols, and toxic metals such as Cd, Cr, Ni, Pb, and Zn (Kuyukina, Krivoruchko, & Ivshina, 2018). Even with these stresses, filamentous fungi exhibit remarkable tolerance and can adapt structurally and metabolically to detoxify both pollutant classes.

Fusarium solani and *Hypocrea lixii* isolated from petrol-station soils degraded pyrene and phenanthrene by more than 70% while tolerating high levels of Cu and Zn (Hong, Park, & Gadd, 2010). *Phanerochaete chrysosporium* removed up to 85 % of PAHs in diesel-polluted soil while simultaneously immobilizing Pb and Ni through phosphate precipitation (Li et al., 2020).

Neurospora crassa has been reported to precipitate Ni- and Ca-carbonates on hyphal surfaces in urea-containing media, forming mineral barriers that localize hydrocarbons and provide secondary carbon sources for fungal metabolism (Li et al., 2017a).

Marine-derived fungi like *Aspergillus*, *Cladosporium*, *Trichoderma*, *Fusarium*, and various basidiomycetes—have evolved osmotolerance and enzyme systems functional under high salinity and pressure (Ceci et al., 2019).

Trichoderma harzianum CBMAI 1677, isolated from ascidian tissues, biodegrades pentachlorophenol (PCP) at concentrations up to 50 mg L^{-1}, demonstrating halotolerance and peroxidase induction (Vacondio et al., 2015).

Marine *Aspergillus* species remove Pb and Cu through biosorption, achieving up to 90 % metal removal from seawater systems (Gazem & Nazareth, 2013).

Penicillium strains decolorize textile dyes such as Reactive Black 5 under saline conditions, aided by osmoprotectant synthesis that stabilizes laccase activity (Ceci et al., 2019).

Marine white-rot fungi (*Bjerkandera*, *Irpex*) also degrade crude-oil fractions and aromatic hydrocarbons via MnP-mediated oxidation, contributing to shoreline restoration.

Comparative Performance of Fungi in Co-Contaminated and Marine Contexts

Fungal Species / Consortium	**Pollutants**	**Environment**	**Mechanism / Enzyme System**	**Removal Efficiency (%)**	**Reference**
Phanerochaete chrysosporium	PAHs + Pb, Ni	Diesel-contaminated soil	LiP, MnP, metal precipitation	85	Li et al., 2020
Fusarium solani, *Hypocrea lixii*	Pyrene, Cu, Zn	Petrol-station soil	Oxidation, chelation	70–80	Hong et al., 2010
Trichoderma harzianum CBMAI 1677	PCP, phenolics	Marine estuary	Peroxidase-mediated oxidation	>70	Vacondio et al., 2015

Aspergillus niger (Marine)	Pb, Cu	Seawater	Biosorption	≈90	Gazem & Nazareth, 2013
Trametes versicolor + *Pseudomonas putida*	Diuron + Cr(VI)	Reactor system	Laccase + bacterial reductase	80 + 60	Hu et al., 2020

Fungal Interactions with Plants and PGPR - The Phytobial Remediation Nexus:

Multi-trophic Interactions which are complex, seen in fungi, bacteria and plants leads to remediation by a single organism in natural and agricultural soils. This integration of organisms known as phytobial remediation, combines the advantages of fungal mycoremediation, bacterial biodegradation, and plant phytoremediation into a synergistic, self-sustaining ecological process (Zhang et al., 2019). Microbial growth stimulated by plant root exudates, fungi enhance nutrient and pollutant mobility through their hyphae, and plant growth-promoting rhizobacteria (PGPR) provide biochemical support through enzyme production and biosurfactant secretion. Together, they create a rhizosphere capable of simultaneous pollutant degradation, metal stabilization, and soil rehabilitation.

Overview of Phytobial Remediation

Component	**Primary Function**	**Mechanistic Contribution to Remediation**
Plants	Phytoextraction and rhizodegradation	Uptake and partial transformation of pollutants; provide exudates that stimulate microbes
Fungi (AMF, WRF, Trichoderma)	Mycoremediation and nutrient exchange	Enzymatic oxidation (LiP, MnP, laccase), metal immobilization, root symbiosis
PGPR	Rhizobacterial facilitation	Biosurfactant and siderophore secretion; auxin production; pollutant solubilization

Consortium (Phytobial system)	Integrated eco-biotechnology	Synergistic pollutant breakdown, soil aggregation, enhanced biomass, improved soil fertility

These systems represent a living technology for reclaiming polluted landscapes and ensuring long-term agricultural sustainability.

Nanofungal and Genetic Engineering Advances in Bioremediation:

Traditional fungal bioremediation has been transformed to multidisciplinary field which results into the integration of biotechnology, material science and environmental engineering, by the help of progress in nanotechnology and molecular genetics.

Normal mycoremediation is efficient but sometimes contained by slow degradation rates, environmental fluctuations, and poor scalability. To correct these wrongs, researchers are combining fungi with nanomaterials and employing genetic engineering tools to enhance enzymatic activity, pollutant specificity, and stress tolerance (Prasad, 2017; Li et al., 2020). These innovations have given rise to next-generation eco-technologies such as nanofungal composites, engineered enzyme systems, and genetically modified strains capable of degrading recalcitrant pollutants at unprecedented rates.

Nanofungal and genetically engineered fungal systems mark a major change in environmental biotechnology. By merging the catalytic versatility of fungi with nanoscale materials and molecular precision tools, these approaches improve traditional limitations of speed, specificity, and robustness. The resulting technologies—magnetically recoverable biosorbents, photocatalytic nanohybrids, and enzyme-enhanced mutant strains—offer sustainable and scalable pathways for tackling complex pollution in industrial, agricultural, and aquatic environments. As research continues to refine these systems, nanobiotechnological mycoremediation stands poised to redefine the future of eco-friendly environmental restoration.

Conclusion:

The information discovered from this study shows that fungal bioremediation—or mycoremediation —is an effective, sustainable, and eco-compatible approach for environmental clean-up. It appears as a transformative, nature-based technology capable of addressing some of the most complex environmental challenges of the 21st century. Fungi contains exceptional biochemical and physiological versatility, enabling them to degrade, transform, or immobilize a broad spectrum of pollutants, including recalcitrant organic compounds, heavy metals, and emerging contaminants. Fungal systems can rival or surpass traditional physicochemical treatments, particularly in terms of sustainability, energy efficiency, and ecological restoration potential (Hu et al., 2020; Vaksmaa et al., 2023). Latest development in nanotechnology and genetic engineering have added details of fungal potential, producing nanofungal composites and engineered strains with increased catalytic and adsorption efficiency. Because of increasing environmental degradation, shifting to fungal bioremediation is not merely an option—it is a necessity. As the world transitions toward circular and regenerative economies, fungi will continue to play an important role as living tools for a cleaner, greener, and more resilient planet.

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