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Fungal Bioremediation: Enzymatic Mechanisms and Applications for Organic and Inorganic Pollutants

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Environmental pollution has emerged as a critical global concern driven by rapid industrialization, urban expansion, and intensive agricultural practices that continuously introduce hazardous contaminants into natural ecosystems [1]. Although conventional remediation technologies are widely applied, they often fail to achieve complete degradation of pollutants and may unintentionally create secondary waste [2], prompting the search for more sustainable solutions. In recent years, fungi have gained attention as promising biological agents for environmental cleanup because of their exceptional enzymatic machinery and adaptive versatility [3]. Their capacity to degrade recalcitrant organic pollutants and immobilize toxic metals makes them valuable tools for addressing complex pollution challenges (Table 1) [4]. This letter highlights the pivotal role of fungi in pollutant transformation, discusses emerging trends in fungal-based remediation technologies, and underscores the need for further exploration of underutilized fungal resources, such as endophytic and marine species. Understanding and advancing fungal-based strategies not only offers a cost-effective and eco-friendly complement to existing methods but also supports global efforts toward ecosystem restoration, sustainable waste management, and a circular bioeconomy.

Table 1: Fungal bioremediation mechanisms.

Mechanisms	Fungal Action/Process	Key Components	Pollutant Target	Outcome/Result
Enzymatic Degradation	Secretion of extracellular enzymes to chemically break down toxins.	Laccases, Manganese Peroxidase (MnP), Lignin Peroxidase (LiP)	Aromatic rings, Polycyclic Aromatic Hydrocarbons (PAHs), Recalcitrant polymers	Cleavage of complex molecules into simpler, less toxic compounds.
Biosorption	Passive, non-metabolic binding of ions to the fungal cell wall (surface adsorption).	Chitin, Glucans, Melanin (cell wall components)	Metal ions (e.g., Lead, Cadmium)	Immobilization of pollutants on the fungal surface.

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Mechanisms	Fungal Action/Process	Key Components	Pollutant Target	Outcome/Result
Bioaccumulation	Active, metabolic uptake of pollutants into the fungal hyphae.	Membrane transporters, Vacuolar sequestration	Metal ions	Internal sequestration and concentration of pollutants within fungal tissues.
Bioprecipitation	Metabolic byproducts (e.g., organic acids) react with metals to form insoluble compounds.	Fungal metabolism, Organic acid production	Soluble metal ions	Formation of insoluble metal salts, causing them to precipitate out of solution.
Mycofiltration	Physical entrapment of solid or particulate contaminants.	Fungal mats, Hyphal networks (nets)	Particulates, Sediments, Heavy metals	Physical removal of particles from water or soil and increased contact time for degradation.
Endophyte-assisted Phytoremediation	Symbiotic partnership with plants; fungi enhance plant uptake of pollutants.	Fungal colonization of plant roots/tissues	Organic pollutants, Metals	Enhanced plant uptake and subsequent degradation/storage of pollutants within the plant.

Fungi are natural decomposers with a vast enzymatic repertoire that allows them to colonize diverse ecological niches. Their ability to degrade lignin, cellulose, and complex xenobiotics stems from an oxidative enzymatic system called lignocellulolytic enzymes, which can break down recalcitrant compounds that many bacteria cannot process [5]. White-rot fungi, for instance, produce a suite of extracellular ligninolytic enzymes, such as laccases (Lac), lignin peroxidases (LiPs), and manganese peroxidases (MnPs), which collectively enable them to attack aromatic rings and complex polymeric structures [6]. These enzymes operate non-specifically, allowing them to oxidize a wide range of pollutants, including textile dyes, pesticides, petroleum hydrocarbons, pharmaceuticals, and plastics [7]. The oxidative mechanism of these enzymes involves the generation of free radicals that attack pollutant molecules, leading to their depolymerization and mineralization [8].

In addition to enzymatic degradation, fungi play a critical role in the removal of inorganic pollutants, such as heavy metals [9,10]. The cell walls of fungal hyphae contain chitin, glucans, proteins, and melanin, which provide binding sites for metal ions [11]. Through biosorption and bioaccumulation, fungi can sequester metals such as cadmium, chromium, lead, and mercury, thereby reducing their mobility and bioavailability in contaminated environments [10]. The mechanism involves ion exchange, complexation, and microprecipitation, which can be enhanced by manipulating culture conditions, such as pH and temperature [12]. Fungal bioremediation can also be integrated into existing waste-management systems. For example, solid-state fermentation using fungal biomass can be employed to treat agro-industrial residues that are rich in lignin and phenolic compounds [13]. The fungal degradation process not only detoxifies waste but also generates value-added products, such as biofertilizers, organic acids, and enzymes [14]. Fungal-based biosorbents derived from agricultural wastes colonized by fungi have also shown great promise for heavy metal removal from aqueous systems, offering a low-cost and sustainable treatment alternative [15].

Endophytic and marine fungi represent emerging frontiers in environmental biotechnology. Endophytic fungi, which reside within plant tissues without causing harm, often produce secondary metabolites and enzymes with unique catalytic properties [16], including laccase, manganese peroxidase, and lignin peroxidase [17]. These metabolites assist in the detoxification of pollutants, and symbiotic interactions with plants enhance phytoremediation efficiency. Marine-derived fungi, which are adapted to high salinity and pressure

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conditions, are another promising source of novel enzymes with improved stability and activity under harsh environmental conditions [18]. Their exploration could significantly expand the range of bioremediation applications, particularly in saline or coastal polluted regions.

Furthermore, the integration of molecular biology and omics technologies is accelerating the discovery of fungal genes and pathways involved in the degradation of pollutants. Genome sequencing and transcriptomic studies have revealed the diversity of oxidative and hydrolytic enzymes in fungi, as well as the regulatory networks that control their expression [19]. Genetic engineering and directed evolution approaches are used to enhance the catalytic efficiency, stability, and specificity of fungal enzymes. For instance, the heterologous expression of fungal laccases in yeast or bacterial systems enables large-scale enzyme production for industrial applications [20]. Similarly, the immobilization of fungal enzymes on solid supports has been developed to improve their reusability and operational stability in bioreactors [21].

The environmental benefits of fungal bioremediation extend beyond the removal of pollutants. By transforming or immobilizing toxic compounds, fungi contribute to soil fertility restoration, water quality improvement, and ecosystem resilience [22]. Moreover, the use of fungal enzymes in industrial processes, such as pulp bleaching, textile processing, and wastewater treatment, reduces dependence on hazardous chemicals and energy-intensive operations [23]. These applications align with the principles of the circular bioeconomy, promoting waste valorization and resource efficiency in the process.

Despite these advances, large-scale implementation of fungal bioremediation faces significant limitations [3]. Fungal degradation is often slow and time-dependent, requiring prolonged incubation to achieve substantial pollutant breakdown, which hampers rapid cleanup [24]. Scaling up from laboratory conditions remains difficult because fungal performance drops sharply in real environments, where fluctuating pH, temperature, salinity, oxygen availability, and pollutant concentrations can suppress enzyme activity or alter metabolic pathways [25]. In outdoor settings, fungi must also survive competition with native microbial communities, resource scarcity, and predation by soil fauna, all of which can reduce their remediation efficiency [26]. Additionally, the deployment of certain strains raises biosafety concerns due to the potential pathogenicity of opportunistic fungi and unintended ecological impacts on indigenous microbes [27]. Addressing these barriers requires careful strain selection, ecological risk assessment, and engineering of stress-tolerant, non-pathogenic variants. Integrating fungi with hybrid treatment systems that combine biological, chemical, and physical approaches may further improve remediation speed, operational stability, and economic feasibility.

In conclusion, fungi are a versatile and sustainable solution to the growing challenge of environmental pollution. Their unique enzymatic machinery, adaptability to diverse environments, and dual capacity for organic degradation and metal sequestration make them valuable in modern bioremediation strategies. However, fully realizing their potential requires more than just laboratory innovation. Future research should deepen our understanding of fungal ecology in contaminated habitats, enhance enzyme production using molecular tools, and prioritize the development of scalable, field-ready technologies [3]. Achieving this will require strong interdisciplinary collaboration, bringing together microbiologists, molecular biotechnologists, environmental engineers, and industrial practitioners to co-design efficient and safe remediation systems. Equally important, scientists must work closely with policymakers, regulatory agencies, and local communities to develop clear biosafety guidelines, provide financial incentives for bioremediation technologies, and embed fungal solutions into national environmental policies. Now is the time to bridge science, industry, and governance to accelerate the adoption of fungal-based remediation and secure a cleaner and more resilient future for our ecosystems.

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