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Mycoremediation Potential of Mushrooms for Environmental Pollution Degradation: A Comprehensive Review of Emerging Fungal Biotechnology for Sustainable Ecosystem Restoration

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ABSTRACT

Environmental pollution caused by industrialization, agriculture, and improper waste disposal has led to the accumulation of toxic pollutants such as hydrocarbons, heavy metals, dyes, pesticides, and plastics in ecosystems. Conventional remediation methods are often expensive and environmentally harmful, creating the need for sustainable alternatives. Mycoremediation, the use of fungi and mushrooms for environmental cleanup, has emerged as an effective and eco-friendly biotechnological approach. Mushrooms produce extracellular enzymes such as laccase, lignin peroxidase, and manganese peroxidase that degrade complex organic pollutants, while fungal biomass removes heavy metals through biosorption and bioaccumulation. Various fungal species including *Pleurotus ostreatus*, *Trametes versicolor*, and *Phanerochaete chrysosporium* have shown significant potential in degrading hydrocarbons, dyes, pesticides, pharmaceuticals, and plastics. Mycoremediation is widely applied in soil remediation, wastewater treatment, agricultural waste management, and air pollution control. Recent advances involving genetic engineering, nanotechnology, omics technologies, and consortium approaches have further improved fungal remediation efficiency. Due to its low cost, environmental compatibility, and sustainability, mycoremediation holds great promise for future environmental restoration and pollution management.

Keywords: Mycoremediation, Biosorption, Bioaccumulation, Nanotechnology, Omics Technologies, Consortium, Sustainability.

1. INTRODUCTION

Rapid industrialization, urban expansion, intensive agricultural practices, mining activities, and indiscriminate disposal of industrial wastes have dramatically increased environmental pollution across the globe. Anthropogenic contaminants released into soil, water, and air ecosystems are causing severe ecological imbalance and posing serious threats to human health. Persistent pollutants such as petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), synthetic dyes, pesticides, plastics, pharmaceutical residues, and toxic heavy metals are highly resistant to natural degradation processes and therefore accumulate in the environment for long periods. These contaminants adversely affect microbial diversity, plant productivity, aquatic organisms, wildlife populations, and overall ecosystem stability. Moreover, prolonged exposure to toxic pollutants has been associated with carcinogenicity, mutagenicity, endocrine disruption, respiratory diseases, neurological disorders, and other chronic health complications in humans (1).

Among the major environmental contaminants, petroleum hydrocarbons generated from oil spills, refinery discharges, and industrial effluents are considered highly hazardous because of their toxic and recalcitrant nature. Similarly, synthetic dyes released from textile, paper, leather, and pharmaceutical industries contaminate aquatic ecosystems by reducing light penetration and dissolved oxygen levels, thereby affecting photosynthetic activity and aquatic biodiversity. Agricultural chemicals such as pesticides and herbicides persist in soils and groundwater, leading to bioaccumulation through food chains. Heavy metals including lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), and arsenic (As) are non-biodegradable pollutants that accumulate in living tissues and cause long-term toxicity. In recent years, plastic waste and microplastic contamination have emerged as another critical environmental issue due to their widespread distribution and extremely slow degradation rates (2).

Traditional physicochemical remediation technologies such as incineration, chemical oxidation, solvent extraction, thermal treatment, and landfilling have been extensively employed for pollution control. However, these methods are often associated with several limitations, including high operational and maintenance costs, energy consumption, incomplete pollutant removal, and generation of secondary toxic by-products. In many cases, conventional remediation approaches merely transfer pollutants from one medium to another rather than completely detoxifying them. Consequently, there has been increasing interest in developing sustainable, eco-friendly, and cost-effective alternatives for environmental cleanup (3).

Bioremediation has emerged as an efficient green technology that utilizes biological organisms to degrade or detoxify environmental contaminants. Various microorganisms including bacteria, algae, plants, and fungi have demonstrated the ability to transform hazardous compounds into less toxic or harmless products. Among these biological agents, fungi have gained particular attention because of their unique physiological and biochemical characteristics. The use of fungi and mushroom-forming species for environmental remediation is known as mycoremediation. This innovative approach exploits the natural metabolic and enzymatic capabilities of fungal mycelia to degrade, accumulate, or immobilize pollutants from contaminated environments (4).

Mushrooms are exceptionally effective bioremediation agents due to their extensive mycelial networks, rapid colonization abilities, and secretion of powerful extracellular enzymes. Unlike bacteria, which often require direct uptake of pollutants into their cells, fungi secrete extracellular oxidative and hydrolytic enzymes capable of breaking down complex organic molecules outside the cell. This feature enables fungi to degrade highly recalcitrant compounds such as lignin, petroleum hydrocarbons, pesticides, dyes, and plastics. The filamentous hyphal structure of fungi allows them to penetrate deep into contaminated substrates, thereby increasing contact with pollutants and enhancing degradation efficiency (5).

2. Concept of Mycoremediation

Mycoremediation refers to the use of fungal mycelia and mushroom-forming fungi to remove or neutralize pollutants from soil, water, and air. The fungal hyphal network acts as a natural biofilter capable of absorbing, accumulating, and enzymatically degrading contaminants. The concept of mycoremediation was widely popularized by Paul Stamets, who highlighted the enormous ecological potential of fungi in restoring contaminated habitats. Through extensive experimental demonstrations, Stamets showed that fungal mycelia could effectively decompose hydrocarbons, filter pathogens from water, and rehabilitate damaged ecosystems. His work significantly contributed to the recognition of fungi as powerful ecological decomposers and environmental restoration agents (6).

Among different fungal groups, white-rot fungi are considered the most efficient organisms for mycoremediation because of their highly nonspecific ligninolytic enzyme systems. Species such as Phanerochaete chrysosporium, Trametes versicolor, and Pleurotus ostreatus produce extracellular oxidative enzymes including laccase, lignin peroxidase (LiP), manganese peroxidase (MnP), and versatile peroxidase. These enzymes are naturally involved in lignin degradation in wood; however, due to their low substrate specificity, they can also oxidize and mineralize a wide range of structurally diverse xenobiotic pollutants. The enzymatic degradation process often converts toxic contaminants into simpler, less harmful molecules such as carbon dioxide, water, and inorganic salts (7).

The remediation process mainly involves:

2.1 Biodegradation

Biodegradation is one of the most important mechanisms involved in mycoremediation, in which fungal enzymes break down complex and toxic pollutants into simpler and less harmful compounds. Mushrooms, particularly white-rot fungi such as Pleurotus ostreatus and Phanerochaete chrysosporium, produce extracellular oxidative enzymes including laccase, lignin peroxidase (LiP), and manganese peroxidase (MnP). These enzymes possess low substrate specificity, enabling them to degrade a wide variety of environmental contaminants such as petroleum hydrocarbons, pesticides, dyes, pharmaceuticals, and plastics. During biodegradation, complex organic molecules are oxidized into smaller intermediates, which are subsequently mineralized into carbon dioxide, water, and other non-toxic substances. The fungal mycelial network enhances pollutant contact and penetration into contaminated substrates, thereby increasing degradation efficiency. Biodegradation is considered an environmentally friendly and sustainable process because it results in the actual destruction of pollutants rather than merely transferring them from one location to another (8).

The generalized biodegradation process can be represented as:

$$\text{Organic Pollutant} + O_2 \xrightarrow{\text{Fungal Enzymes}} CO_2 + H_2O + \text{Simpler Metabolites}$$

2.2 Biosorption

Biosorption refers to the passive binding and adsorption of pollutants, particularly heavy metals, onto the surface of fungal biomass. The fungal cell wall is composed of polysaccharides such as chitin, glucans, proteins, and lipids that contain functional groups including amino, carboxyl, hydroxyl, phosphate, and sulfhydryl groups. These functional groups interact with metal ions through ion exchange, complexation, coordination, and electrostatic attraction mechanisms. Mushrooms such as Ganoderma lucidum and Agaricus bisporus exhibit remarkable biosorption capacities for toxic metals like lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), and arsenic (As). Biosorption is advantageous because it is rapid, cost-effective, and can occur even in non-living fungal biomass. Furthermore, fungal biosorbents can often be regenerated and reused, making the process economically feasible for wastewater treatment and heavy metal remediation applications (9).

The biosorption mechanism can be expressed as:

$$\text{Fungal Biomass} + M^{n+} \rightarrow \text{Biomass} - M^{n+}$$

where M^{n+} represents metal ions.

2.3 Bioaccumulation

Bioaccumulation is an active metabolic process in which fungal cells absorb and accumulate contaminants within their intracellular structures. Unlike biosorption, which occurs on the cell surface, bioaccumulation involves the transport of pollutants across the cell membrane into the cytoplasm through energy-dependent mechanisms. Mushrooms can accumulate heavy metals, radionuclides, and organic pollutants inside their cells, where these substances may be detoxified, compartmentalized, or bound to intracellular proteins and peptides such as metallothioneins. Species like Pleurotus florida and Lentinula edodes have demonstrated considerable capacities for intracellular accumulation of toxic metals from contaminated soils and water. Bioaccumulation plays a significant role in reducing pollutant concentrations in the environment; however, proper disposal of contaminated fungal biomass is necessary to prevent re-entry of pollutants into ecosystems. This mechanism is particularly important for the remediation of metal-contaminated industrial effluents and mining sites (10).

The intracellular uptake process may be summarized as:

$$M^{n+}_{\text{external}} \rightarrow M^{n+}_{\text{intracellular}}$$

2.4 Biotransformation

Biotransformation is the biochemical conversion of toxic pollutants into less toxic, less mobile, or environmentally safer compounds through fungal metabolic activities. In this process, fungal enzymes chemically modify pollutants through oxidation, reduction, hydrolysis, methylation, or dehalogenation reactions. The transformed products are often more biodegradable and less harmful than the parent compounds. Mushrooms are capable of transforming various xenobiotic compounds including pesticides, dyes, pharmaceuticals, endocrine-disrupting chemicals, and industrial solvents. White-rot fungi such as Trametes versicolor are especially efficient in biotransformation due to their powerful oxidative enzyme systems. For example, highly toxic aromatic compounds can be converted into simpler organic acids and alcohols with reduced toxicity. Biotransformation is considered highly valuable because it detoxifies pollutants without generating large quantities of secondary waste. In many cases, it also serves as an intermediate step before complete biodegradation and mineralization (11).

The generalized biotransformation reaction can be represented as:

$$\text{Toxic Compound} \xrightarrow{\text{Fungal Metabolism}} \text{Less Toxic Metabolite}$$

3. Mechanisms of Pollutant Degradation by Mushrooms

3.1 Extracellular Enzymatic System

Mushrooms possess an efficient extracellular enzymatic system that plays a major role in the degradation of environmental pollutants. These fungi secrete powerful ligninolytic enzymes outside their cells, allowing them to break down structurally complex and recalcitrant compounds present in contaminated environments. The primary enzymes involved in this process include laccase, lignin peroxidase (LiP), manganese peroxidase (MnP), and versatile peroxidase. Laccase catalyzes the oxidation of phenolic compounds and synthetic dyes by utilizing molecular oxygen, whereas lignin peroxidase oxidizes non-phenolic aromatic compounds and cleaves complex lignin structures through hydrogen peroxide-mediated reactions. Manganese peroxidase converts Mn^{2+} into Mn^{3+}, which acts as a diffusible oxidizing agent capable of degrading various organic pollutants. Versatile peroxidase combines the catalytic properties of both lignin peroxidase and manganese peroxidase, enabling it to oxidize a wide range of substrates. These enzymes exhibit low substrate specificity, meaning they can act on numerous structurally different compounds, including pesticides, polycyclic aromatic hydrocarbons (PAHs), chlorinated phenols, dyes, petroleum hydrocarbons, and pharmaceutical residues. Through oxidative reactions, the extracellular enzymatic system transforms toxic pollutants into simpler, less harmful metabolites, thereby contributing significantly to mycoremediation and environmental detoxification (12).

Ligninolytic Reaction System

$$\text{Lignin} + O_2 \xrightarrow{\text{Laccase/LiP/MnP}} CO_2 + H_2O + \text{degraded metabolites}$$

3.2 Biosorption Mechanism

Biosorption is an important mechanism through which mushrooms remove heavy metals and toxic pollutants from contaminated environments. Fungal cell walls are primarily composed of chitin, glucans, proteins, and other polysaccharides that contain numerous functional groups capable of binding metal ions. These functional groups include carboxyl (–COOH), amino ($–NH_2$), hydroxyl (–OH), phosphate ($–PO_4^{3–}$), and sulfhydryl (–SH) groups, which interact with metal ions through processes such as ion exchange, adsorption, chelation, and complex formation. During biosorption, heavy metal ions present in wastewater or soil are attracted to the fungal biomass surface and become attached to the cell wall components. This process can be represented as:

$$\text{Fungal Biomass} + M^{n+} \rightarrow \text{Biomass} - M^{n+}$$

where M^{n+} represents heavy metal ions such as Pb^{2+} (lead), Cd^{2+} (cadmium), Hg^{2+} (mercury), and Cr^{6+} (chromium). The fungal biomass acts as a natural biosorbent, immobilizing toxic metals and reducing their bioavailability and toxicity in the environment. Biosorption is considered an eco-friendly, cost-effective, and highly efficient remediation method because it can remove metals even at low concentrations without producing harmful secondary pollutants. This mechanism makes mushrooms highly valuable in the treatment of industrial effluents, wastewater, and heavy metal-contaminated soils (13).

4. Types of Pollutants Degraded by Mushrooms

4.1 Hydrocarbon Pollution

Petroleum hydrocarbons released from oil spills, refinery wastes, industrial discharge, and leakage from storage tanks are among the most serious environmental pollutants affecting soil and aquatic ecosystems. These pollutants contain toxic compounds such as polycyclic aromatic hydrocarbons (PAHs), benzene, toluene, xylene, diesel, and other petroleum-derived hydrocarbons that persist in the environment for long periods and pose significant risks to human health, plants, animals, and microorganisms. Many hydrocarbon compounds are carcinogenic, mutagenic, and highly resistant to natural degradation. Mushrooms and filamentous fungi have shown remarkable potential in the biodegradation of these pollutants due to their extensive mycelial network and powerful extracellular oxidative enzymes. Important fungal species involved in hydrocarbon degradation include *Pleurotus ostreatus*, *Trametes versicolor*, and *Aspergillus niger*. These fungi produce ligninolytic enzymes such as laccase, lignin peroxidase, and manganese peroxidase, which can attack the complex aromatic structures of hydrocarbons. Through fungal activity, toxic petroleum compounds are transformed into simpler and less harmful substances, thereby reducing environmental toxicity and restoring contaminated ecosystems (14).

4.1.1 Mechanism of Hydrocarbon Degradation

The degradation of hydrocarbons by mushrooms occurs through a series of oxidative and enzymatic reactions. Initially, extracellular enzymes secreted by fungi oxidize complex hydrocarbon molecules, particularly aromatic rings present in PAHs and petroleum compounds. This oxidation process introduces oxygen into the hydrocarbon structure, converting it into alcohols, aldehydes, organic acids, and other intermediate metabolites. Fungal mycelia further metabolize these intermediates through intracellular enzymatic pathways, ultimately breaking them down into simple inorganic compounds such as carbon dioxide and water. During this process, fungi utilize hydrocarbons as a carbon and energy source for growth and metabolism. The extensive hyphal network of fungi also enhances contact with pollutants, improving degradation efficiency in contaminated soils and water. Thus, mushrooms contribute significantly to the detoxification and mineralization of petroleum hydrocarbons through enzymatic oxidation, transformation, and complete biodegradation (15).

4.2 Heavy Metal Remediation

Heavy metals are among the most hazardous environmental pollutants because they are non-biodegradable, persistent, and capable of accumulating in soil, water, plants, animals, and ultimately the food chain. Industrial activities such as mining, electroplating, battery manufacturing, textile processing, pesticide application, and metallurgical operations release significant amounts of toxic metals into the environment. Common heavy metals removed by fungi include lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), and arsenic (As), all of which can cause severe health problems such as neurological disorders, kidney damage, carcinogenic effects, and disruption of biological systems. Mushrooms have emerged as efficient biological agents for heavy metal remediation due to their high metal-binding capacity and adaptability to contaminated environments. Species such as *Ganoderma lucidum*, *Pleurotus florida*, and *Agaricus bisporus* are widely studied for their ability to absorb, accumulate, and detoxify heavy metals from polluted soils and wastewater. The fungal mycelial network provides a large surface area for metal interaction, while the cell wall components containing chitin, glucans, and proteins facilitate strong binding of toxic metal ions. As a result, mushrooms significantly reduce metal toxicity and help restore environmental quality through eco-friendly and cost-effective remediation processes (16).

4.2.1 Mechanism of Heavy Metal Remediation

Fungi remove heavy metals primarily through biosorption and intracellular sequestration mechanisms. In biosorption, metal ions present in contaminated environments bind to functional groups such as carboxyl, amino, hydroxyl, phosphate, and sulfhydryl groups located on the fungal cell wall. This passive process immobilizes metals on the biomass surface and reduces their mobility and bioavailability. After surface adsorption, some metal ions are transported into fungal cells through active uptake mechanisms. Inside the cells, fungi detoxify and store metals through intracellular sequestration by binding them with proteins, peptides, or vacuolar components. Certain fungi also produce metal-chelating compounds and antioxidants that protect cellular structures from metal-induced oxidative stress. Through these combined processes, toxic heavy metals are immobilized, accumulated, and detoxified, thereby preventing their spread in the environment and reducing ecological and health risks (17).

4.3 Synthetic Dye Degradation

Synthetic dyes released from textile, paper, leather, cosmetic, and printing industries are major environmental pollutants that contaminate aquatic ecosystems. Large quantities of coloured effluents containing azo dyes and other recalcitrant colorants are discharged into rivers and water bodies without adequate treatment, leading to severe ecological and health problems. These dyes reduce light penetration in water, inhibit photosynthesis in aquatic plants, and may produce toxic, mutagenic, or carcinogenic compounds. Many synthetic dyes are highly stable and resistant to conventional physical and chemical treatment methods because of their complex aromatic molecular structures. Mushrooms and ligninolytic fungi have demonstrated remarkable potential in the biodegradation and detoxification of these pollutants through their extracellular oxidative enzyme systems. Common dyes degraded by fungi include Congo red, methylene blue, malachite green, and reactive black. Fungal species such as *Pleurotus ostreatus*, *Trametes versicolor*, and *Phanerochaete chrysosporium* are especially effective in dye remediation. These fungi produce ligninolytic enzymes capable of attacking complex chromophoric structures present in synthetic dyes, resulting in decolorization and detoxification of industrial effluents. Therefore, mushroom-based bioremediation offers an eco-friendly, cost-effective, and sustainable approach for the treatment of dye-contaminated wastewater (18).

4.3.1 Mechanism of Synthetic Dye Degradation

The degradation of synthetic dyes by mushrooms occurs mainly through extracellular enzymatic oxidation. Among the ligninolytic enzymes, laccase plays a dominant role in oxidative dye degradation. Laccase catalyzes the oxidation of dye molecules by removing electrons from their aromatic structures, leading to the breakdown of chromophoric groups responsible for color. Other enzymes such as lignin peroxidase and manganese peroxidase may also assist in the degradation process by generating reactive radicals that attack complex dye molecules. Initially, the fungal enzymes destabilize azo bonds and aromatic rings present in synthetic dyes, converting them into smaller intermediate compounds. These intermediates are further metabolized through fungal biochemical pathways and eventually mineralized into simpler, non-toxic products such as carbon dioxide, water, and inorganic salts. In addition to enzymatic degradation, fungal biomass can adsorb dye molecules onto the cell surface, enhancing dye removal efficiency. Through oxidation, decolorization, adsorption, and mineralization, mushrooms effectively detoxify synthetic dyes and reduce the environmental impact of industrial wastewater (19).

4.4 Pesticide and Herbicide Removal

The extensive use of pesticides and herbicides in modern agriculture has led to severe contamination of soil, groundwater, and surrounding ecosystems. Many agricultural chemicals persist in the environment for long periods because of their stable chemical structures and resistance to natural degradation. These pollutants can accumulate in crops, water bodies, and food chains, posing serious risks to human health, animals, and beneficial microorganisms. Common contaminants include organophosphate pesticides, chlorinated pesticides, and herbicides such as DDT, atrazine, chlorpyrifos, and glyphosate. Exposure to these compounds has been associated with neurological disorders, endocrine disruption, carcinogenic effects, and ecological imbalance. Mushrooms, particularly white-rot fungi, have shown significant potential in the biodegradation and detoxification of agricultural pollutants due to their highly efficient ligninolytic enzyme systems. Fungal species such as *Pleurotus ostreatus*, *Trametes versicolor*, and *Phanerochaete chrysosporium* produce extracellular oxidative enzymes capable of attacking the complex aromatic and chlorinated structures of pesticides and herbicides. Through fungal activity, these persistent chemicals are transformed into simpler and less toxic compounds, thereby reducing environmental pollution and improving soil and water quality (20).

4.4.1 Mechanism of Pesticide and Herbicide Removal

The removal of pesticides and herbicides by mushrooms primarily occurs through extracellular enzymatic degradation and metabolic transformation. White-rot fungi secrete ligninolytic enzymes such as laccase, lignin peroxidase, and manganese peroxidase, which possess low substrate specificity and can oxidize a wide variety of xenobiotic compounds. These enzymes initiate degradation by attacking aromatic rings, chlorinated groups, and complex chemical bonds present in pesticides and herbicides. During the process, large toxic molecules are broken into smaller intermediate metabolites through oxidation, dechlorination, hydroxylation, and cleavage reactions. The intermediate compounds are then further metabolized within fungal cells and eventually mineralized into carbon dioxide, water, and other less harmful products. In some cases, fungal biomass may also adsorb pesticide molecules onto the cell surface, enhancing pollutant removal efficiency. Through these combined enzymatic and metabolic processes, mushrooms effectively detoxify agricultural chemicals and contribute to the restoration of contaminated environments (21).

4.5 Plastic and Microplastic Degradation

Plastic accumulation has become one of the most serious global environmental problems due to the excessive production and disposal of synthetic polymer materials. Plastics such as polyethylene, polyurethane, polypropylene, and polystyrene are highly resistant to natural degradation and persist in the environment for hundreds of years. Over time, larger plastic materials break down into microplastics, which contaminate soil, freshwater, marine ecosystems, and even food chains. These pollutants pose significant threats to wildlife, aquatic organisms, and human health because they can accumulate toxic chemicals and enter biological systems. Conventional methods of plastic disposal, including incineration and landfilling, often generate additional environmental hazards. Recent studies have demonstrated that certain fungi and mushrooms possess the ability to partially degrade plastics and microplastics through enzymatic and oxidative processes. Notable fungal species involved in plastic degradation include *Pleurotus tuber-regium* and *Aspergillus tubingensis*. These fungi produce extracellular enzymes capable of attacking complex polymer structures, thereby contributing to the fragmentation and biodegradation of synthetic plastics. Fungal mycelia can also colonize plastic surfaces, increasing contact between enzymes and polymer materials and enhancing degradation efficiency. Consequently, mushrooms are gaining increasing attention as eco-friendly biological agents for sustainable plastic waste management and environmental remediation (22).

4.5.1 Mechanism of Plastic and Microplastic Degradation

The degradation of plastics and microplastics by fungi occurs mainly through extracellular enzymatic oxidation and polymer breakdown. Fungi secrete oxidative enzymes such as laccases, peroxidases, esterases, and hydrolases that attack the long-chain polymer structures of plastics. Initially, fungal hyphae colonize the plastic surface and form biofilms, allowing enzymes to penetrate and weaken the polymer matrix. Oxidative reactions introduce oxygen-containing functional groups into the plastic structure, leading to depolymerization and fragmentation of complex polymers into smaller molecules. In the case of polyurethane, fungal enzymes hydrolyze ester and urethane bonds, whereas polyethylene degradation involves oxidation of carbon chains and formation of intermediate compounds such as alcohols, aldehydes, and organic acids. These smaller intermediates are further utilized by fungi as carbon and energy sources and are eventually converted into simpler products such as carbon dioxide, water, and biomass. Although fungal degradation of plastics is generally slower than degradation of natural organic matter, these biological processes offer promising and environmentally sustainable approaches for reducing plastic and microplastic pollution (23).

5. Major Mushroom Species Used in Mycoremediation

S. No.	Mushroom Species	Major Pollutants Degraded	Key Enzymes / Components	Mechanism of Remediation	Major Functions in Mycoremediation
1	*Pleurotus ostreatus*	Hydrocarbons, textile dyes, pesticides, PAHs	Laccase, Manganese peroxidase (MnP), Versatile peroxidase	Extracellular enzymatic oxidation and biodegradation of aromatic compounds	Degrades petroleum hydrocarbons, decolorizes dyes, detoxifies pesticides, and improves soil bioremediation
2	*Phanerochaete chrysosporium*	Lignin, PAHs, chlorinated compounds, industrial wastes	Lignin peroxidase (LiP), MnP	Oxidative cleavage of complex aromatic structures using ligninolytic enzymes	Mineralizes recalcitrant pollutants and detoxifies industrial contaminants
3	*Trametes versicolor*	Textile dyes, pharmaceuticals, phenols, endocrine disruptors	Laccase, LiP	Oxidative degradation of xenobiotic compounds through extracellular enzymes	Decolorizes industrial effluents and removes pharmaceutical pollutants
4	*Ganoderma lucidum*	Heavy metals, industrial effluents	Biosorption proteins, polysaccharides	Biosorption and intracellular sequestration of metal ions	Immobilizes toxic metals and reduces heavy metal toxicity
5	*Agaricus bisporus*	Heavy metals and metal-contaminated wastes	Cell wall adsorbents, chitin, glucans	Adsorption and accumulation of metals on fungal biomass	Removes and accumulates toxic metal ions from polluted environments
6	*Pleurotus tuber-regium*	Plastics, microplastics, hydrocarbons	Laccase, esterases, peroxidases	Enzymatic depolymerization and oxidation of plastic polymers	Contributes to biodegradation of polyethylene and polyurethane materials
7	*Aspergillus niger*	Petroleum hydrocarbons, dyes, heavy metals	Oxidases, hydrolases, biosorptive proteins	Enzymatic degradation and biosorption	Removes hydrocarbons and adsorbs toxic metal ions from wastewater
8	*Aspergillus tubingensis*	Polyurethane, plastic waste, microplastics	Polyurethane-degrading enzymes, esterases	Surface colonization and enzymatic polymer breakdown	Enhances degradation of synthetic plastic materials
9	*Pleurotus florida*	Heavy metals, pesticides, dyes	Laccase, MnP, biosorptive cell wall components	Biosorption and oxidative degradation	Removes heavy metals and detoxifies organic pollutants
10	*Lentinula edodes* (*Shiitake*)	Phenolic pollutants, dyes, pesticides	Laccase, MnP	Oxidative biodegradation of aromatic pollutants	Detoxifies phenolic industrial contaminants and agricultural chemicals
11	*Irpex lacteus*	Pharmaceutical residues, dyes, lignin wastes	MnP, LiP, laccase	Enzymatic oxidation and mineralization	Degrades persistent pharmaceutical and dye pollutants
12	*Bjerkandera adusta*	Synthetic dyes, chlorinated phenols, PAHs	Laccase, peroxidases	Radical-mediated oxidative degradation	Removes toxic aromatic pollutants

					and industrial dye contaminants
13	*Coprinellus disseminatus*	Industrial dyes, phenolic compounds	Laccase	Extracellular oxidation of aromatic compounds	Decolorizes wastewater and degrades phenolic pollutants
14	*Pycnoporus sanguineus*	Textile dyes, pesticides, phenols	High laccase-producing system	Oxidative enzymatic degradation	Efficient dye decolorization and detoxification of industrial effluents
15	*Stropharia rugosoannulata*	Agricultural pollutants, pesticides, hydrocarbons	Peroxidases, cellulolytic enzymes	Biodegradation and nutrient cycling	Restores contaminated soils and supports ecological remediation (25,26)

6. Applications of Mycoremediation

Mycoremediation has emerged as an eco-friendly and sustainable biotechnology for the management of environmental pollutants. Mushrooms and fungi possess extensive mycelial networks and powerful extracellular enzymes that enable them to degrade, transform, or immobilize a wide range of contaminants present in soil, water, air, and industrial wastes. In addition to pollutant removal, fungi contribute to nutrient recycling, soil restoration, and ecosystem recovery. Due to their versatility, low operational cost, and minimal environmental impact, mycoremediation technologies are increasingly being applied in agriculture, wastewater treatment, industrial pollution control, and waste management.

6.1 Soil Remediation

Fungi play a significant role in restoring contaminated soils by degrading toxic pollutants and improving soil fertility. Industrial discharge, pesticide overuse, mining activities, and petroleum spills introduce hazardous compounds such as hydrocarbons, pesticides, heavy metals, and xenobiotics into soils. Mushroom-forming fungi produce extracellular enzymes capable of degrading these pollutants into simpler and less toxic compounds. Their extensive mycelial network penetrates deeply into soil, increasing contact with contaminants and enhancing biodegradation efficiency. In addition to pollutant removal, fungi improve soil structure, aeration, water retention, and nutrient cycling through the decomposition of organic matter. Certain fungi also immobilize heavy metals through biosorption and bioaccumulation, thereby reducing metal toxicity and bioavailability.

6.2 Wastewater Treatment

Mycofiltration and fungal-based wastewater treatment systems are highly effective in removing pollutants from industrial and municipal effluents. Textile industries, pharmaceutical plants, paper mills, and chemical industries discharge wastewater containing dyes, phenols, pharmaceuticals, heavy metals, pesticides, and pathogenic microorganisms. Fungal mycelia and extracellular enzymes such as laccase, lignin peroxidase, and manganese peroxidase degrade these contaminants through oxidative reactions. Fungi can also adsorb toxic metal ions and trap suspended particles within their mycelial network. In mycofiltration systems, fungal biomass acts as a natural biofilter that removes pollutants while improving water quality. Certain fungal species are additionally capable of reducing bacterial contamination and pathogenic load in wastewater.

6.3 Agricultural Waste Management

Mycoremediation plays an important role in the management and recycling of agricultural residues. Large quantities of lignocellulosic wastes such as straw, husks, sawdust, sugarcane bagasse, corn stalks, and crop residues accumulate after agricultural activities and are often burned, causing air pollution. Mushrooms possess lignocellulolytic enzymes capable of degrading cellulose, hemicellulose, and lignin present in agricultural wastes. Through fungal decomposition, these residues are converted into nutrient-rich compost and organic fertilizers that improve soil fertility and crop productivity. Species such as *Pleurotus ostreatus* and *Volvariella volvacea* are commonly cultivated on agricultural wastes, simultaneously producing edible mushrooms and reducing environmental waste. This process supports sustainable agriculture, waste recycling, and circular bioeconomy practices.

6.4 Air Pollution Control

Certain fungi are used in biofiltration systems for the removal of airborne pollutants and toxic gases. Industrial emissions, vehicular exhaust, and chemical processes release volatile organic compounds (VOCs), hydrocarbons, and airborne toxins into the atmosphere, contributing to respiratory disorders and environmental pollution. Fungal biofilters contain fungal mycelia immobilized on organic substrates, where airborne pollutants are trapped and degraded enzymatically. Fungi metabolize VOCs and convert them into less harmful compounds such as carbon dioxide, water, and biomass. Their large surface area and extensive hyphal growth enhance pollutant adsorption and degradation efficiency. Mycofiltration systems are therefore increasingly applied in industrial exhaust treatment and indoor air purification.

6.5 Biodegradation of Petroleum Hydrocarbons

Mycoremediation is widely applied in the cleanup of oil-contaminated environments. Mushrooms degrade petroleum hydrocarbons, diesel, benzene, toluene, and polycyclic aromatic hydrocarbons (PAHs) through extracellular oxidative enzymes. White-rot fungi such as *Pleurotus ostreatus* and *Trametes versicolor* are particularly efficient in transforming toxic hydrocarbons into simpler metabolites. This application is important in the remediation of oil spills, refinery waste sites, and contaminated marine and terrestrial ecosystems.

6.6 Heavy Metal Removal

Fungi are highly effective biosorbents for the removal of toxic heavy metals from contaminated water and soils. Their cell walls contain chitin, glucans, proteins, and functional groups capable of binding metals such as lead, cadmium, mercury, chromium, arsenic, copper, and nickel. Through biosorption, bioaccumulation, and intracellular sequestration, mushrooms immobilize toxic metals and reduce their environmental mobility. This application is extensively used in mining waste treatment, industrial effluent management, and restoration of contaminated agricultural land.

6.7 Synthetic Dye and Industrial Effluent Treatment

Textile and dye industries generate large volumes of coloured wastewater containing recalcitrant dyes and aromatic compounds. Fungal enzymes such as laccase and peroxidases degrade azo dyes, methylene blue, malachite green, and other industrial colorants through oxidative reactions. Mycoremediation reduces colour intensity, toxicity, and chemical oxygen demand (COD) in industrial wastewater, making it safer for environmental discharge.

6.8 Plastic and Microplastic Degradation

Certain fungi can colonize and partially degrade synthetic plastics and microplastics through enzymatic oxidation and depolymerization. Fungal species such as *Aspergillus tubingensis* and *Pleurotus tuber-regium* produce enzymes capable of breaking down polyethylene and polyurethane polymers into smaller biodegradable compounds. This emerging application of mycoremediation offers promising solutions for reducing persistent plastic waste and microplastic pollution.

6.9 Bioremediation of Pesticides and Herbicides

Fungi degrade agricultural chemicals such as DDT, atrazine, chlorpyrifos, and glyphosate through extracellular oxidative enzymes. White-rot fungi convert these toxic compounds into less harmful metabolites through oxidation, dechlorination, and mineralization reactions. This application helps reduce groundwater contamination and minimizes the ecological impact of excessive pesticide usage.

6.10 Radioactive Waste and Toxic Compound Removal

Some fungal species exhibit tolerance to radioactive environments and can absorb radionuclides and toxic elements from contaminated sites. Melanized fungi are capable of surviving in radiation-rich environments and may contribute to the bioremediation of radioactive wastes and nuclear accident sites. Fungal biomass can also bind toxic chemicals and radioactive isotopes, reducing their spread in the environment.

6.11 Ecosystem Restoration and Reforestation

Fungi support ecological restoration by improving soil fertility, nutrient availability, and plant growth. Mycorrhizal fungi form beneficial associations with plant roots, enhancing nutrient uptake and helping vegetation establish in degraded environments. Mycoremediation combined with reforestation programs accelerates ecosystem recovery in polluted and deforested areas.

6.12 Sustainable Bioenergy and Resource Recovery

Fungal degradation of organic wastes contributes to biofuel production and resource recovery. Agricultural and industrial biomass degraded by fungi can be converted into biogas, bioethanol, and other renewable energy products. Simultaneously, fungal-treated residues can be utilized as animal feed, compost, or soil conditioners, supporting sustainable waste valorization and circular economy systems (28,29).

7. Advantages of Mycoremediation

- Eco-friendly and sustainable
- Low operational cost
- Minimal secondary pollution
- High efficiency against recalcitrant pollutants
- Ability to grow on agricultural waste
- Simultaneous waste valorisation and remediation (30)

8. Limitations and Challenges

Despite its potential, mycoremediation faces several challenges:

- Slow degradation under field conditions
- Sensitivity to environmental factors
- Scale-up difficulties
- Competition with indigenous microorganisms
- Incomplete mineralization of some pollutants
- Risk of toxic metabolite formation (31)

9. Recent Advances in Mycoremediation

Recent developments in biotechnology, environmental engineering, and microbial ecology have significantly improved the efficiency and applicability of mycoremediation. Modern research focuses on enhancing fungal degradation capacity, improving pollutant removal efficiency, and integrating fungal systems with advanced technologies for sustainable environmental management. Advances in genetic engineering, nanotechnology, microbial consortia, and circular bioeconomy approaches have expanded the potential applications of fungi in pollution control and ecosystem restoration. These innovations are making mycoremediation more effective, economically feasible, and suitable for large-scale environmental remediation programs.

9.1 Genetic Engineering

Genetic engineering has emerged as an important tool for improving the remediation potential of fungi. Scientists are developing genetically modified fungal strains with enhanced production of ligninolytic enzymes such as laccase, lignin peroxidase, and manganese peroxidase. Through recombinant DNA technology and gene editing techniques, fungi can be engineered to tolerate higher pollutant concentrations and degrade contaminants more rapidly. Overexpression of specific degradation genes improves the breakdown of hydrocarbons, dyes, pesticides, plastics, and pharmaceutical compounds. Genetic modifications also enhance fungal resistance to environmental stress factors such as extreme pH, salinity, heavy metals, and toxic chemicals. These engineered fungi demonstrate greater remediation efficiency and adaptability under industrial and field conditions, making them promising candidates for advanced environmental cleanup technologies.

9.2 Nanotechnology Integration

The integration of nanotechnology with mycoremediation has opened new possibilities for enhanced pollutant removal. Nanoparticles possess high surface area, catalytic activity, and adsorption capacity, which improve fungal degradation efficiency. Nanoparticle-assisted fungal remediation enhances the adsorption, transformation, and mineralization of contaminants such as heavy metals, dyes, hydrocarbons, and pesticides. Metallic nanoparticles including silver, iron oxide, titanium dioxide, and zinc oxide are commonly combined with fungal biomass or enzymes to increase pollutant interaction and oxidative degradation rates. Nanomaterials can also support enzyme immobilization, improve fungal stability, and accelerate electron transfer during degradation reactions. This combined approach significantly increases remediation speed and effectiveness while reducing operational costs

9.3 Consortium Approaches

Consortium-based remediation strategies involve the combined use of fungi, bacteria, algae, and plants to achieve synergistic pollutant removal. Different microorganisms possess complementary metabolic pathways that enhance degradation efficiency when working together. Fungi break down large and complex organic pollutants into simpler intermediates, which are then further degraded by bacteria and other microorganisms. Mycorrhizal fungi also improve plant growth and increase phytoremediation efficiency by enhancing nutrient uptake and pollutant tolerance. These integrated systems are highly effective in the treatment of mixed contaminants such as hydrocarbons, pesticides, heavy metals, and industrial wastewater. Consortium approaches improve biodegradation rates, ecological stability, and adaptability in contaminated environments, making them highly suitable for large-scale remediation projects.

9.4 Circular Bioeconomy

The concept of circular bioeconomy has significantly increased the sustainability of mycoremediation technologies. Spent mushroom substrate (SMS), which remains after mushroom cultivation, is now widely utilized for composting, biofertilizer production, animal feed supplements, bioenergy generation, and environmental cleanup. SMS retains active fungal enzymes, organic matter, and microbial communities capable of degrading pollutants and improving soil quality. Instead of being discarded as waste, SMS is reused in agriculture, wastewater treatment, and bioremediation applications, promoting resource recycling and waste valorization. This approach reduces environmental waste generation and supports sustainable agricultural and industrial practices.

9.5 Enzyme Immobilization Technology

Recent studies have focused on immobilizing fungal enzymes onto solid supports such as nanoparticles, polymers, activated carbon, and biochar. Immobilized enzymes exhibit greater stability, reusability, and resistance to environmental fluctuations compared to free enzymes. Laccase and peroxidase immobilization improves the degradation of dyes, pharmaceuticals, pesticides, and phenolic compounds in industrial wastewater. Enzyme immobilization also allows continuous treatment processes and reduces operational costs in large-scale remediation systems.

9.6 Mycofiltration Systems

Advanced mycofiltration systems use fungal mycelia as biological filters for removing pollutants from water and air. Fungal biofilters efficiently trap suspended particles, pathogens, heavy metals, dyes, and organic pollutants. Recent innovations involve the development of portable mycofiltration units and hybrid biofiltration systems integrated with activated carbon or nanomaterials. These systems are increasingly applied in wastewater treatment plants, stormwater management, and indoor air purification technologies.

9.7 Omics and Molecular Approaches

Recent advances in omics technologies have significantly enhanced the understanding of fungal biology and pollutant degradation mechanisms, making them valuable tools for improving mycoremediation efficiency. Omics approaches—including genomics, transcriptomics, proteomics, and metabolomics—provide comprehensive insights into the molecular processes involved in fungal growth, enzyme production, stress adaptation, and contaminant degradation. Unlike traditional microbiological techniques, which investigate individual genes or proteins, omics technologies simultaneously analyze thousands of biological molecules, allowing researchers to obtain a systems-level understanding of fungal responses to environmental pollutants. These advanced molecular techniques are facilitating the identification of highly efficient fungal strains and supporting the development of targeted strategies for environmental remediation. Genomics focuses on the complete genetic makeup of fungi and enables the identification of genes responsible for pollutant degradation, enzyme synthesis, stress tolerance, and metabolic regulation. Whole-genome sequencing has revealed numerous genes encoding ligninolytic enzymes such as laccase, lignin peroxidase (LiP), manganese peroxidase (MnP), and versatile peroxidase, which are responsible for the degradation of a wide range of recalcitrant pollutants.

9.8 Biochar–Fungus Integrated Systems

The integration of **biochar technology** with **mycoremediation** has emerged as an innovative and highly effective approach for the remediation of contaminated soils and wastewater. This integrated strategy combines the excellent adsorption capacity of biochar with the powerful biodegradation abilities of fungi, resulting in enhanced removal of a wide range of environmental pollutants. Biochar is a carbon-rich, porous material produced through the pyrolysis of agricultural residues, forestry wastes, and other biomass under limited oxygen conditions. Owing to its high surface area, porous structure, and abundance of functional groups, biochar acts as an excellent support material for fungal growth while simultaneously adsorbing pollutants from contaminated environments. The synergistic interaction between biochar and fungal mycelia significantly improves remediation efficiency compared with the use of either technology alone.

9.9 Artificial Intelligence and Predictive Modeling

Artificial Intelligence (AI) and computational modeling have emerged as powerful tools for advancing mycoremediation by improving the understanding, prediction, and optimization of fungal-mediated pollutant degradation. Traditional mycoremediation research often relies on extensive laboratory experiments and field trials, which are time-consuming, labour-intensive, and expensive. AI technologies, particularly machine learning (ML), deep learning (DL), artificial neural networks (ANNs), and predictive analytics, enable researchers to analyze large and complex environmental datasets, identify hidden patterns, and accurately predict fungal performance under diverse environmental conditions. These computational approaches significantly accelerate research while reducing the need for repeated experimental trials. Machine learning algorithms can predict fungal growth rates, mycelial colonization patterns, enzyme production, biodegradation efficiency, and pollutant removal capacity by analyzing environmental variables such as temperature, pH, moisture content, nutrient availability, oxygen concentration, pollutant type, and contaminant concentration.

9.10 Bioplastic and Sustainable Material Development

Recent advances in fungal biotechnology have expanded the applications of mycoremediation beyond environmental cleanup to the development of biodegradable materials and sustainable bioplastics. Researchers are increasingly exploring the use of fungal mycelium, the vegetative network of thread-like hyphae that forms the main body of fungi, as a renewable and eco-friendly raw material for manufacturing biodegradable products. Unlike conventional petroleum-based plastics, which require hundreds of years to degrade and contribute significantly to environmental pollution, mycelium-based materials are produced from natural, renewable resources and decompose rapidly under composting conditions without releasing toxic residues. This innovative approach not only addresses the growing problem of plastic waste but also provides a sustainable alternative for material production. The production of mycelium-based materials involves cultivating selected fungal species, such as Pleurotus ostreatus, Ganoderma lucidum, and Trametes versicolor, on agricultural and industrial lignocellulosic wastes including rice straw, wheat straw, corn stover, sawdust, sugarcane bagasse, cotton waste, and other crop residues. During growth, the fungal mycelium penetrates and binds these substrates together through an extensive network of hyphae, forming lightweight, durable, and biodegradable composite materials.

9.11 Electro-Mycoremediation

Electro-mycoremediation is an emerging and innovative environmental remediation technology that integrates mycoremediation with electrochemical processes to enhance the removal and degradation of environmental pollutants. This approach combines the natural biodegradation capabilities of fungi with the application of low-intensity electric fields, resulting in improved contaminant mobility, increased fungal metabolic activity, and enhanced production of extracellular enzymes. The synergistic interaction between fungal metabolism and electrochemical stimulation significantly improves the efficiency of pollutant removal from contaminated soils, sediments, and wastewater.

9.12 Field-Scale and Industrial Applications

Recent advances in environmental biotechnology have successfully transformed mycoremediation from a laboratory-based research concept into a practical technology with significant field-scale and industrial applications. Earlier studies primarily focused on evaluating the pollutant-degrading capabilities of fungi under controlled laboratory conditions. However, improvements in fungal cultivation techniques, bioreactor design, enzyme engineering, and environmental monitoring have enabled the implementation of pilot-scale and commercial remediation systems. These developments demonstrate that fungal technologies can effectively address complex environmental pollution problems under real-world conditions, making mycoremediation an increasingly viable alternative to conventional physicochemical remediation methods. One of the most significant developments is the use of fungal bioreactors for the treatment of industrial wastewater. These systems provide controlled conditions that optimize fungal growth, enzyme production, aeration, pH, temperature, and nutrient availability, thereby maximizing pollutant degradation efficiency (32,33).

10. Future Perspectives

Mycoremediation is gaining increasing global attention as a sustainable and eco-friendly approach for environmental cleanup. Although significant progress has been achieved in laboratory and pilot-scale studies, further advancements are necessary to improve the large-scale applicability, efficiency, and commercialization of fungal remediation technologies. Future research should focus on discovering efficient fungal species, understanding molecular degradation pathways, developing advanced remediation systems, and integrating fungal technologies into existing environmental management practices. Strengthening scientific research, industrial collaboration, and environmental policies will help establish mycoremediation as a major component of sustainable pollution control and ecological restoration.

10.1 Identification of Novel Fungal Species

Future research should prioritize the identification and characterization of novel fungal species with enhanced biodegradation potential. Many unexplored fungi present in forests, marine ecosystems, extreme environments, and contaminated habitats may possess unique enzymes and metabolic pathways capable of degrading complex pollutants. Screening and isolation of these fungi can lead to the discovery of highly efficient strains for the removal of hydrocarbons, plastics, pesticides, dyes, pharmaceuticals, and heavy metals. Novel fungal species may also demonstrate greater tolerance to harsh environmental conditions such as extreme pH, salinity, temperature, and toxic contaminant concentrations. The exploration of fungal biodiversity therefore offers immense potential for expanding the scope and effectiveness of mycoremediation technologies.

10.2 Omics-Based Understanding of Degradation Pathways

Advanced omics technologies such as genomics, transcriptomics, proteomics, and metabolomics will play a crucial role in understanding fungal degradation mechanisms at the molecular level. These approaches can identify genes, enzymes, proteins, and metabolic pathways involved in pollutant degradation and stress adaptation. Omics-based studies help reveal how fungi interact with contaminants, regulate enzyme production, and transform toxic compounds into less harmful metabolites. Such knowledge can support the development of genetically improved fungal strains with enhanced remediation efficiency and environmental adaptability. In addition, bioinformatics and systems biology tools will facilitate the prediction and optimization of fungal biodegradation processes for various pollutants.

10.3 Large-Scale Field Trials

Although numerous laboratory studies have demonstrated the effectiveness of mycoremediation, large-scale field trials are essential for evaluating its practical applicability under real environmental conditions. Field studies help assess fungal survival, pollutant degradation efficiency, environmental adaptability, and long-term ecological impacts in contaminated soils, wastewater systems, and industrial sites. Factors such as climate, soil composition, pollutant concentration, and microbial competition can influence remediation performance in natural environments. Therefore, future research should focus on designing pilot-scale and industrial-scale remediation projects to validate fungal technologies and establish standardized operational protocols for commercial implementation.

10.4 Development of Fungal Bioreactors

The development of advanced fungal bioreactors represents an important future direction for industrial-scale mycoremediation. Fungal bioreactors provide controlled environmental conditions that optimize fungal growth, enzyme production, and pollutant degradation efficiency. These systems can be designed for continuous treatment of industrial wastewater, petroleum contaminants, dyes, pharmaceuticals, and agricultural wastes. Future bioreactor technologies may incorporate immobilized fungal enzymes, nanomaterials, automated monitoring systems, and microbial consortia to improve treatment performance and operational stability. The advancement of cost-effective and scalable fungal bioreactors will significantly enhance the commercial application of mycoremediation technologies.

10.5 Integration with Wastewater Treatment Plants

Integrating fungal remediation technologies into existing wastewater treatment plants can improve the removal of recalcitrant pollutants that are difficult to eliminate through conventional treatment methods. Many industrial and municipal wastewater systems are unable to efficiently degrade dyes, pharmaceuticals, pesticides, endocrine disruptors, and heavy metals. Fungal enzymes such as laccase and peroxidases can complement existing biological and chemical treatment processes by targeting these persistent contaminants. Future wastewater treatment systems may incorporate fungal biofilters, mycofiltration units, and fungal bioreactors as additional treatment stages.

10.6 Policy Support for Green Remediation Technologies

Strong environmental policies and governmental support are essential for promoting the adoption of mycoremediation and other green remediation technologies. Future environmental management strategies should encourage the use of sustainable biological approaches instead of solely relying on expensive and environmentally harmful physical or chemical remediation methods. Governments and regulatory agencies can support mycoremediation through research funding, industrial incentives, environmental regulations, and public awareness programs. Establishing guidelines for fungal remediation applications, biosafety assessment, and waste management will also facilitate commercialization and field implementation.

10.7 Sustainable Environmental Restoration

Mycoremediation holds tremendous promise for achieving sustainable environmental restoration and reducing ecological risks associated with industrial pollutants. Fungi possess unique enzymatic systems capable of degrading complex contaminants while simultaneously improving soil quality, nutrient cycling, and ecosystem stability. Unlike conventional remediation methods, fungal technologies are cost-effective, environmentally friendly, and capable of utilizing agricultural and industrial wastes as substrates. Future integration of mycoremediation with biotechnology, nanotechnology, artificial intelligence, and circular bioeconomy approaches will further expand its applications in pollution control, waste recycling, renewable resource recovery, and ecosystem rehabilitation (34,35).

11. CONCLUSION

Mycoremediation is an eco-friendly and sustainable approach for the removal of environmental pollutants using fungi and mushrooms. Through extracellular enzymes and biosorption mechanisms, fungi can effectively degrade hydrocarbons, dyes, pesticides, plastics, and other toxic compounds while also removing heavy metals from contaminated environments. Various mushroom species have demonstrated significant potential in soil remediation, wastewater treatment, agricultural waste management, and air pollution control. Recent advances in biotechnology, nanotechnology, and molecular research have further enhanced the efficiency of fungal remediation systems. Although challenges related to large-scale application still exist, mycoremediation offers a cost-effective and environmentally safe alternative for pollution control and sustainable environmental restoration. Future research focusing on novel fungal species, molecular degradation pathways, fungal bioreactor development, and integration with existing wastewater treatment systems will significantly strengthen the practical implementation of mycoremediation technologies. With continued scientific advancement and policy support, mycoremediation holds immense potential as an eco-friendly and economically viable strategy for sustainable environmental restoration, pollution control, and ecological conservation in the future.

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