Is Fungi the Key to Bioremediation of Contaminated Soil?

Puja Rani*
Department of Molecular Biology and Biotechnology, CCS HAU, Hisar Haryana, India
pujavijay44@gmail.com

*__Corresponding author__
Puja Rani
PhD Research Scholar
Department of Molecular Biology and Biotechnology,
CCS HAU, Hisar Haryana, India

Abstract

Currently, there is a growing number of human-made and industrial activities that are progressively expanding. These activities result in the discharge of many types of environmental harmful pollutants, including organic, inorganic, and metallic pollutants, into the soil. These hurt living creatures. The natural repair and removal of these toxicants is not feasible, so their dissociation is imperative using biologically efficient, environmentally safe, and cost-effective ways. Various fungal species have a crucial function in transforming several harmful contaminants into harmless forms via their mycelia and extracellular enzymes. Nevertheless, further research endeavors should be intensified on this burgeoning and environmentally conscious method. Additional research should focus on identifying fungal species that are capable of effectively remedying soil pollutants and can withstand stressful situations. Furthermore, to address and treat the polluted soil, there is a need for wider adoption and implementation of this sophisticated method across several interdisciplinary domains.

Keywords: Bioremediation, Environment, Fungi, Pollutants, Soil

1. Introduction:

Soil is an integral component of our environment, upon which the growth and development of a varied range of living species heavily rely. Currently, the soil environment is becoming heavily polluted daily as a result of civilization, urbanization, and industrialization. A multitude of ecological issues are occurring due to toxins that inflict significant damage to the Earth and all forms of life, rendering it a topic of worldwide concern [1]. Anthropogenic and industrial activities are causing contamination of agricultural areas and soil biodiversity. Although pesticides, herbicides, and insecticides are employed in agricultural fields to enhance productivity, this ultimately results in the contamination of soil, air, and water. Despite the widespread use of numerous physical-chemical procedures, their high cost and detrimental consequences pose risks to both human life and the environment [2]. Several studies have identified alternative methods for removing toxins, one of which is bioremediation. Bioremediation involves the use of microorganisms and their by-products to eliminate harmful pollutants and minimize their negative impact on the environment [3]. Bioremediation is an emerging discipline of environmental restoration that uses organisms to reduce the concentration and toxicity of pollutants such as organic pollutants, heavy metals, pesticides, and dyes. It is a cost-effective removal technology. Fungi are eukaryotic creatures that are found everywhere and may thrive in various environmental situations [4]. Mycoremediation, also known as fungal remediation, is a bioremediation technique that harnesses the power of fungi to break down harmful contaminants in the environment. Fungi are more significant in the process of bioremediation of pollutants compared to other microorganisms [5]. This is due to their ability to rapidly colonize environments by penetrating soils with their hyphae, allowing them to reach soil toxins more efficiently than other microorganisms [6].

2. Pollutants

Pollutants are undesirable substances that contaminate the environment and upset both the non-living and living components of ecosystems. The main sources of pollutants in the soil are environmental pollution and industrialization. These pollutants include persistent toxic chemicals, xenobiotics, recalcitrant, radioactive materials, heavy metals, salts, and organic pollutants [7]. They have detrimental effects on the growth of plants and animals. Fungi secrete a wide range of extracellular enzymes, which can effectively repair various contaminants in polluted soil [8]. The classification of important soil contaminants is as follows:

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2.1 Inorganic pollutants or heavy metals: The issue of metallic pollution is increasingly alarming. Various industrial activities, such as leather tanning, electroplating, and paint production, discharge wastewater that is then utilized for agricultural uses. This practice has long-term detrimental consequences on the ecosystem, particularly through the food chain [9]. Fungi are referred to as hyper-accumulators due to their ability to amass high concentrations of harmful contaminants in their fruiting bodies [10]. Several fungal species have proven to be highly effective in the remediation of heavy metals such as Cadmium (Cd) and Chromium (Cr).

2.2 Organic pollutants: Organic pollutants are substances that are introduced into the soil environment as a result of industrial and agricultural operations, as well as incorrect waste management. These pollutants contribute to soil pollution and contamination [11]. These pollutants and xenobiotic compounds encompass fertilizers, pesticides, insecticides, and herbicides, among others. Persistent organic compounds refer to carbon-based contaminants and organic molecules that remain in the environment for an extended period [12-13]. Polyaromatic hydrocarbons such as naphthalene and benzopyrene, petrochemicals, insecticides, various solvents, and metals are important organic pollutants due to their continuous introduction into the soil. Organic compounds consist of lengthy chains of hydrogen and carbon groups, and their structure is similar to that of lignin and cellulose. Multiple lignicolous fungi possess the ability to excrete abundant extracellular enzymes, which facilitate the breakdown and disintegration of organic molecules and environmental organic waste within our ecosystem [14].
Soil contamination is a significant issue caused by the release of harmful substances resulting from human activity. In ancient times, people used soil as a handy method of trash disposal. However, numerous studies have revealed that this practice poses a severe problem. Toxic chemicals and soil contaminants can spread to various parts of the environment and contaminate the soil [15]. The primary sources of soil pollution include the improper disposal of biomedical waste, the discharge of industrial and nuclear waste, mining activities, accidental oil spills, smelting processes, acid rain, disruptions in subterranean storage tanks, the dumping of sludge and fuel, intensive farming practices, and the use of pesticides, herbicides, and fertilizers [15]. Remediating soil pollutants is a laborious and costly endeavor that necessitates expertise in computer modeling, geology, chemistry, hydrology, geographical information systems, and industrial chemistry [16]. Hence, the process of remediating and separating polluted soil is widely regarded as a highly effective approach. The primary pollutants responsible for soil pollution can be described as follows:

2.2.1 Heavy metal contamination in the soil

Heavy metals are metallic elements having an atomic number greater than 20. The metal conversion mechanism is a prevalent process in soil, involving many metals. Heavy metals are introduced into the soil environment through both natural and human activities [17]. The prevalent heavy metals include arsenic (As), cadmium (Cd), mercury (Hg), chromium (Cr), strontium (Sr), cesium (Cs), uranium (U), copper (Cu), lead (Pb), zinc (Zn), cobalt (Co), manganese (Mn), and nickel (Ni). Certain heavy metals, including Co, Cu, Mn, Ni, and Zn, are essential micronutrients for plant development and growth. In contrast, heavy metals such as Pb, Hg, and Cd have no specific biological purpose. Nevertheless, elevated levels of specific heavy metals can hurt several forms of life, including plants, animals, and microorganisms. The primary natural sources of heavy metals include rock erosion, volcanic activities, and mineral weathering. On the other hand, the main anthropogenic sources are electroplating, mining, smelting, industrial discharge, and the use of pesticides, herbicides, fertilizers, and biosolids in agriculture [18].

2.2.2 Organic contamination in the soil

Hazardous organic contaminants were introduced into the soil through the emission of industrial wastewater, solid waste, and other human-made sources. The harmful substances mentioned, such as fertilizers, pesticides, herbicides, and petrochemicals, are classed as Persistent Organic Pollutants. They accumulate in the food chain of species and have detrimental impacts on the ecosystem [19]. Organometallic compounds, such as tributyltin (TBT), and pesticides, like dichlorodiphenyltrichloroethane (DDT), are classified as persistent organic pollutants (POPs). At present, 22 organic compounds are categorized as Persistent Organic Pollutants. Some of these compounds are manufactured directly, while others are produced as by-products during industrial processes. Polychlorinated biphenyls (PCB), hexachlorobenzene (HCB), polychlorinated dibenzo-p-dioxins (PCDD), polyaromatic hydrocarbons (PAHs), polychlorinated dibenzofurans (PCDF), and brominated flame retardants are specific instances of substances that are produced as a result of chemical interactions [20].

3. Bioremediation: detoxification of contaminants

Soil contamination caused by harmful substances is one of the most significant environmental issues worldwide. Bioremediation is a cost-effective, simple, and environmentally benign way of remedying harmful contaminants, which is among the most prevalent biological, chemical, and physical strategies [21]. Bioremediation is the process of using living organisms, such as bacteria, fungi, algae, and plants, to break down and remove harmful compounds and pollutants. Furthermore, it serves as a remediation technique employed to address environmental pollutants in their natural habitat by preventing additional contamination and generating harmless by-products [22]. During the process of bioremediation, specific inorganic and organic pollutants can undergo degradation and detoxification. As a result, the level of contamination is greatly reduced. Additionally, microorganisms are capable of utilizing xenobiotic toxins as sources of nutrients and energy, promoting their future growth [23]. Microbes possess remarkable resilience in harsh environmental conditions, exhibit diverse metabolic pathways, restore the original natural state of their surroundings, are present everywhere in the environment, and serve as an efficient means of decontaminating soil, water, and sediment pollutants by preventing further pollution [24]. The potential of fungi in sustainable agriculture, environmental applications, and nano-technology. Bioremediation procedures are categorized into two techniques: in situ and ex-situ bioremediation, based on the breakdown and removal of pollutants. The in-situ bioremediation technique involves the use of microorganisms to remove hazardous compounds at the same area where the pollution occurred. On the other hand, the ex-situ remediation technique involves the biodegradation of contaminated material at a different location, distinct from the contaminated site [25].

4. **Mycoremediation** (bioremediation with fungi)

Mycoremediation refers to the utilization of fungi in the bioremediation process, using fungal-based technology to eliminate harmful environmental toxins that negatively impact living organisms. This technique has become increasingly effective and efficient in recent years [26]. Mycoremediation is the process by which several fungal species aid in the complete breakdown of harmful pollutants into harmless chemicals, including CO_2, H_2O, N_2, and HCl. Mycoremediation is an environmentally benign and sustainable approach used for actively remediating contaminated environments. Fungi are regarded as significant biological agents for the bioremediation of pollutants due to their unique shape and metabolic capabilities. However, the Fungi were already being considered in the 1980s for their ability to remove contaminants and contribute to the growth of environmental biotechnology [27]. Since then, extensive research has been conducted on the practical and theoretical aspects of mycoremediation about both soil and water. Fungi species are widely distributed, making them applicable in several fields worldwide. Fungi exhibit remarkable adaptability to diverse environmental conditions through spore dispersal and the production of several enzymes. In addition, mycelium is utilized for the expulsion of harmful substances from polluted areas like as industrial effluent treatment plants. Mycoremediation is considered a reliable approach for the elimination of soil contaminants due to the ability of the fungus to break down organic compounds without the need for extraction. This process reduces the risk of pollutants spreading and accumulating in the ecological food chain. Fungi possess the superior capacity for soil bioremediation compared to other microorganisms such as bacteria and yeasts [28]. Fungi possess distinctive traits that make them suitable for mycoremediation of various soil contaminants. These traits include their ability to colonize soil, withstand high levels of toxins, and facilitate the movement of minerals, nutrients, and water.

4.1 Mycoremediation mechanisms and processes

Microorganisms are present everywhere in nature and can be found in a wide range of environmental circumstances. Fungi possess the ability to acclimate to harsh climatic conditions and stressful environments. They can convert poisonous molecules, organic pollutants, hazardous substances, metal ions, and complex hydrocarbons into less harmful and simpler forms. The mycoremediation technique involves several mechanisms and processes, including biosorption, mobilization, immobilization, biotransformation, and bioaccumulation [29].

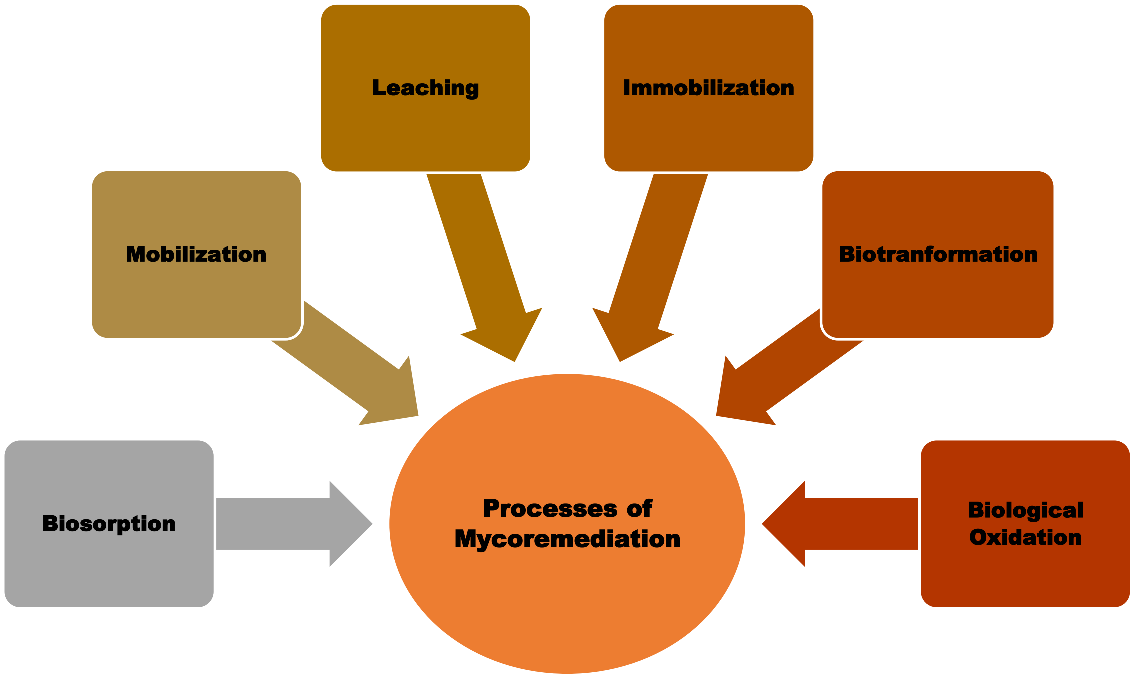

Figure 1: Process of Mycoremediation

4.1.1 Biosorption is a rapid and reversible physicochemical process that involves several mechanisms, including precipitation, ion exchange, adsorption, reduction, chelation, and interaction with functional groups on the surface of cells. These mechanisms enable the uptake of harmful contaminants from non-living biological sources [30]. This technique involves the use of a solid phase called a biosorbent and a liquid phase known as a solvent. The fungal biomass in mycoremediation plays a crucial role because of its high concentration of cell wall components, which serve as effective biosorbents. Electrostatic interactions occur between the cell wall of fungi and metal ions, facilitating the biosorption of several metals including cadmium, copper, zinc, uranium, and cobalt. *Ganoderma lucidum* and *Aspergillus niger* are fungal species that carry out chromium biosorption through the ion exchange mechanism [31].

4.1.2 Mobilization Microorganisms can activate toxic contaminants by some mechanisms such as chelation by siderophores, leaching, methylation, alkylation, and redox transformations: Chelation by siderophores low-molecular-weight iron-chelating legends can bind with additional metals including chromium, gallium, magnesium and manganese [32].

4.1.3 Leaching production of low-molecular-weight organic acids that provide protons and metal-complexing organic acid anions after breakdown. Methylation involves the assimilation of methyl groups that are enzymatically transferred to metal and form different metalloids [33]. Alkylation involves alkyl group transformation from one molecule to another as alkyl carbonation, a free radical, and a carbanion form. Redox transformations use reduction and/or oxidation processes for the mobilization of metals, metalloids, and organometallic compounds by activating microbes.

4.1.4 Immobilization approach is utilized by microbes to reduce the mobility of contaminants and to modify their physical or chemical characteristics by the restriction of physical interaction among the toxic contaminants. In this mechanism of mycoremediation, two approaches such as solidification and stabilization are involved [34]. Through this method, the contaminated material is mixed with water and stabilizer and produces a solidified matrix. Then some chemicals are introduced in the process so that the heavy metals can precipitate in the form of metal hydroxides. Some factors like water and temperature are involved in this mechanism of immobilization [35].

4.1.5 Biotransformation In this approach of biotransformation the microorganisms modify the surrounding environment through catalysis, oxidation, methylation, and demethylation. Other mechanisms like precipitation and biological oxidation/reduction are also involved in the interaction of metal ions: Bio precipitation In the process when organic carbon mineralizes into carbon dioxide and oxygen is reduced into water enhances the pH and alkalinity of the microbial cell environment, and with the formation of excess bicarbonate the precipitation of metal ions occur such as metal hydroxides Me(OH)x or metal carbonate $MeCO_3$ [36].

4.1.6 Biological oxidation/reduction Microorganisms with the help of various enzymes catalyze the reduction of heavy metals such as As(V) to As (III), Cr(VI) to Cr(III), Fe(III) to Fe(II), Mn(VI) to Mn(II), Mo(VI) to Mo(IV), Se(VI) to Se(IV), and U(VI) to U(IV) [37].

5. Mechanism for mycoremediation of organic contaminants

The remediation of organic contaminants in soils and their mechanism is the same as the lignin degradation. In these mechanisms, various fungal enzymes are involved to oxidize the organic compounds directly and indirectly, including Lacasses, Lignin-peroxidase, Manganese Peroxidase, and Versatile peroxidase [38].

5.1 The mechanism for the mycoremediation of metal ions Various mechanisms are adopted by fungi to mycoremediation metal ions in soil because they have the better capability to bind with metal ions and build up the metal ion complex inside the cell, can endure the metal uptake and immobilize the metal ions; after that detoxify the toxic metal ions to nontoxic forms by some processes such as demethylation, methylation, oxidation, reduction, and volatilization [39]. Some indigenous microbe with fungi also takes part in the mineralization of contaminants in the form of carbon dioxide and water. In yeast, *Rhodotorula mucilaginosa* the bioaccumulation complex as well as free silver ions and bioabsorption of lead, takes place by metabolism-dependent and metabolism-independent processes. Fungi like Candida can remove metal ions as well as radionuclides present in the environment [40].

5.2 Factors affecting mycoremediation of contaminated soil: The physical and chemical properties of soil, like temperature, pH, moisture content, chemical nature, redox potential, soil type, and presence of macro and micronutrient nutrients significantly accelerate the growth of microorganisms and effective bioremediation. Other factors include concentration, type, accessibility, bioavailability, mobility, and toxicity of contaminants; also influence the metabolic activity of microbes in so [41]. Pollutant degradation depends on factors like types of microorganisms, their genetic characteristics, metabolic potential, life cycle of fungal agents, fungal species, surface active and chelating agents, and extracellular and intracellular enzymatic systems. In mycoremediation, the filamentous fungi (e.g. *Aspergillus and Penicillium spp*.) with metabolic pathways accelerate the production of mycotoxins to remove different pollutants such as pharmaceutical compounds. Fungi can tolerate under variety of environmental conditions for efficient mycoremediation including low pH, temperature, oxygen level, sunlight, nutrients and moisture content, and soil geochemistry [42]. Some of the main factors responsible for efficient mycoremediation are described as follows

5.2.1 Contaminant concentration: The concentration of contaminants also affects the mycoremediation process by influencing the activity of microbes. At high concentrations of contaminants, the microbes got affected due to various toxic effects, while at low concentrations, the secretion of some degradative enzymes got deactivated. Compared to bacteria, filamentous fungi can resist high concentrations of contaminants, synthesize numerous enzymes, and make a mycelia network [43].

5.2.2 Contaminant bioavailability: The bioavailability of contaminants also plays an important role in the optimization and acceleration of mycoremediation of contaminants. In the mycoremediation of aged PAH-contaminated soils, degradation is affected by contaminant bioavailability. Many researchers have demonstrated that contaminant bioavailability affects the ability of fungal species to produce biosurfactants. Some fungi such as species Penicillium and Aspergillus can produce biosurfactants. In the field of environmental protection, microbial biosurfactants have lots of applications such as biodegradation of oil-contaminated soil, and oil spills [44].

5.2.3 Water availability: The availability of water in the soil affects the successful biodegradation of contaminants by providing accessibility for oxygen supply, enzyme production, growth of fungi, microbial behavior, microbial utilization, contaminant binding, and distribution in the soil [45]

5.2.4 Enzyme reactions The enzyme reactions are involved in the mycoremediation process and eliminate most of the other factors. In the biodegradation of contaminants, both extracellular as well as intracellular enzymes are produced by different fungi and bacteria for the acceleration of the reaction rate [46].

5.2.5 Effects of temperature The effect of temperature is an important factor for microbial growth and effective bioremediation of pollutants. reported that the optimum temperature for the mycoremediation process ranges from 25 to 30°C. The degradation rate of organic contaminants is higher in tropical soils as compared to temperate soil depending upon temperature. It has been demonstrated that the half-life of organic contaminants increases as the temperature decreases [47].

5.2.6 Soil pH: The pH of the soil is an important factor in determining the biodegradation rate. It has been demonstrated that at high soil pH, the organic contaminants degradation rate increased, while at low soil pH, the remediation decreased. In some studies, the pH of the soil plays a critical role in the mycoremediation of DDT and petroleum contaminants and enhances the bioremediation of these organic contaminants at alkaline pH [48].

5.2.7 Effects of relative humidity The relative humidity is usually maintained at above 60% for mycoremediation of contaminated soils [49]. reported the relative humidity for mycoremediation was 70%, by was 60%, by was between 6070%, while and reported the higher relative humidity values of 8595% and 7080%.

5.2.8 Soil nutrient The soil nutrient is a major factor that accelerates bioremediation rate. Additions of proper amount of nutrients in soil enhance the bioremediation process of contaminants by stimulating the growth rate and activity of soil microorganisms [50]

5.2.9 Soil moisture is necessary for the growth, activity, and function of microbes that circulate water and nutrients in and out of the cell. Additionally, if soil moisture is enhanced it causes saturation of the soil and conflicts with the oxygen transfer, which eventually affects microbial respiration by reducing the available oxygen quantity. The moisture content in soil depends on the soil type, texture, porosity, and water-holding capacity [51].

5.2.10 Type of soil The type of soil also determines the biodegradation of soil contaminants, as small size relates large surface area to volume ratio of soil and leads to enhanced biological, chemical, and physical properties for microbial activity [52].

5.3 **Contaminated soil remediation** by fungi In Mycoremediation (fungal-based technique) degradation and mineralization of soil pollutants such as heavy metals, petroleum hydrocarbons, polycyclic aromatic hydrocarbons, xenobiotics, insecticides, and pesticide residues, performed by different groups of fungi. Which can break down long-chain toxic chemicals into simplified forms. Keeping this in iew, the role of fungi in mycoremediation for biodegradation of toxic contaminants of soil into simpler and less toxic forms is being discussed in this section [53]. Fungal species capable of biodegrading toxic pollutants from environment like *Candida spp., Pichia spp., Rhodotorula spp., Clavispora spp., Debaryomyces spp., Leucosporidium spp., Yarrowia spp., Sporidiobolus spp., Rhodosporidium spp., Sporobolomyces spp., Stephanoascus spp*

5.4 Mycoremediation of contaminated soil pollutants with fungal enzymes

Fungi can produce different types of enzymes and have the unique property of dissociating polymeric organic compounds such as chitin, keratin, melanin, lignin, and cellulose. After the breakdown of toxic substances, some soluble products are again absorbed and utilized by internal enzymes. Additional microorganisms also benefit from these substrates other than primary fungal oxidizers and make complex interactions. In the mycoremediation of several toxic pollutants in contaminated soil, numerous exoenzymes, and secondary metabolites are generated into the substrate by fungi. The lignin-degrading fungi contain lots of enzymes for lignin degradation and these enzymes have the important property for degradation of persistent organic pollutants, pesticides, and herbicides which are responsible for soil contamination [54]. Fungi species produce enzymes for the biodegradation of contaminants in soil and provide new approaches in the field of bioremediation. Among all the fungi groups, the white-rot fungi can play an important role in the complete degradation of different pollutants with lots of extracellular enzymes such as laccases, lignin peroxidases, versatile peroxidases, manganese-dependent peroxidases, H_2O_2 generating oxidases and dehydrogenases [55]. Some fungal enzymes and their role in soil pollutants mycoremediation. Some of the main species of WRF responsible for efficient mycoremediation of contaminants are *Agaricus bisporus, Phanerochaete chrysosporium, Pleurotus ostreatus, Pleurotus tuber-regium, Trametes versicolor, Pleurotus pulmonarius, Irpex lacteus, Lentinula.*

5.5 Mycoremediation of heavy metals: cell walls like carboxylic, phosphate, and amine or sulfhydryl groups, which provide negative charge and help to bind with metals. Some fungal species of Agaricus, Amanita, Aspergillus, Boletus, Cortinarius, Leccinum, Mucor, Penicillium, Phellinus, Suillus, and Trichoderma can remove different heavy metals in soil efficiently. Microbial leaching of some metals like iron, aluminum, silicon, and calcium by some fungal species Aspergillus, Alternaria, and Cladosporium have also been observed, the fungal species can re-precipitate silicon and calcium oxalate in contaminated sites. Several extracellular enzymes like ligninolytic and cellulolytic enzymes are secreted by saprotrophic basidiomycetes and white rot fungi utilized for heavy metals degradation. The activity of several enzymes is positively regulated by increasing and decreasing concentrations of heavy metals, for example at low concentrations of some metals like Cd, Cu, and Hg, the activity of the Mn-peroxidase enzyme decreases, and if the concentration level of metals increases the enzyme activity of Mn-peroxidase increased. It has also been reported that, while increasing the concentration of Cu, the activity of enzymes like isoenzyme and laccase increases, but the addition of Hg decreases laccase activity [56].

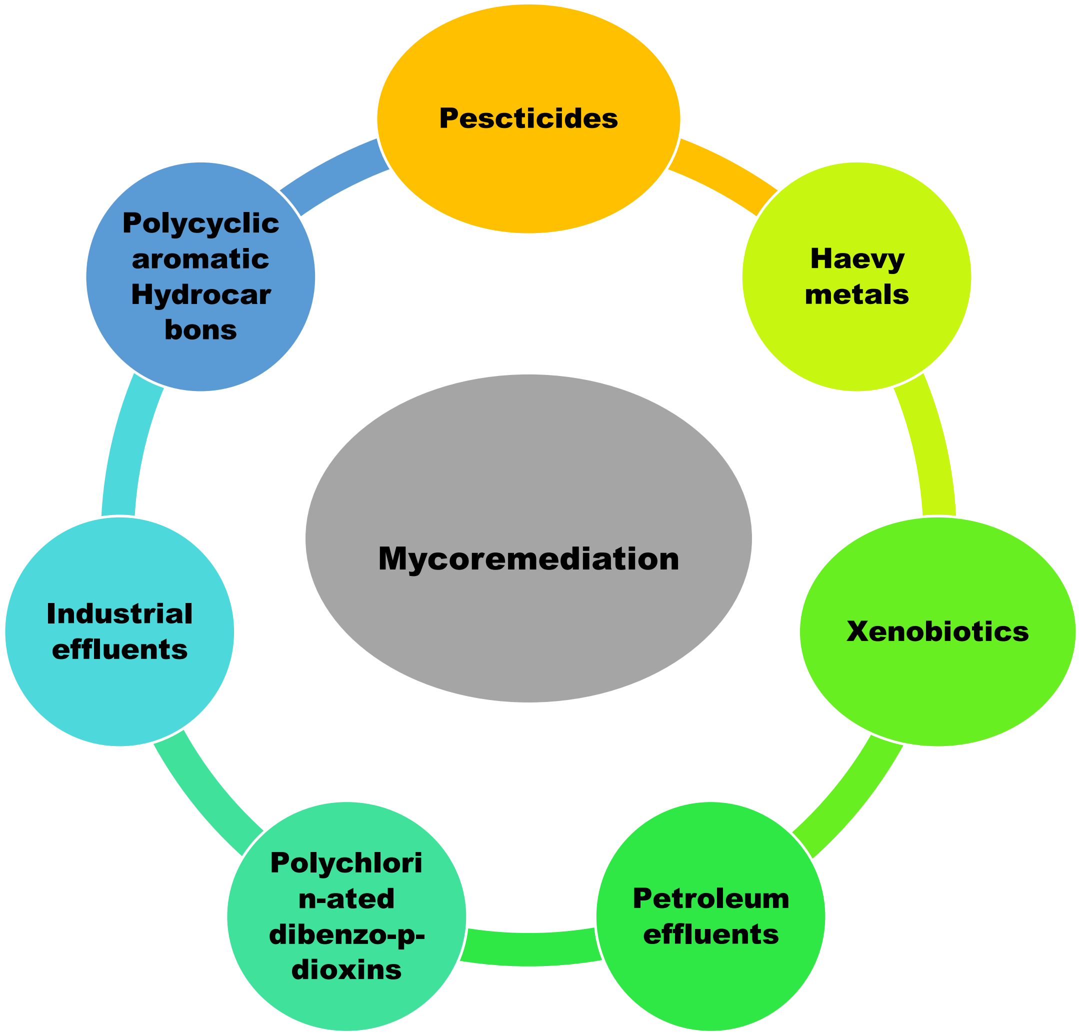

Figure 2: Bioremediation by Fungus

5.6 Mycoremediation of pesticide residue: Pesticides like insecticides, fungicides, nematicides, and herbicides, are used intensively in agriculture and their residues persist in soil for a long time because of less degradation and complex structure, which causes adverse effects on living beings. Fungi have a high bioremediation potential to degrade pesticide residues with their enzymatic system. Fungal enzymes like lignin-degrading enzymes, laccase, oxidoreductases, and peroxidases have the prominent capacity to remove pesticides and insecticide residues from contaminated sites. Some species of fungi like *Dichomitus squalens, Agrocybe semiorbicularis, Coriolus versicolor, Flammulina velutipes, Auricularia auricula, Phanerochaete chrysosporium, and Pleurotus ostreatus*, can degrade different types of pesticides includes aldrin, atrazine, chlordane, dichlorodiphenyltrichloroethane (DDT), dieldrin, diuron, gamma-hexachlorocyclohexane, heptachlor, lindane, metalaxyl, mirex, and terbuthylazine, etc. has been stated the mycoremediation of simazine herbicide in contaminated soil by Penicillium steckii fungi [57].

5.7 Mycoremediation of petroleum-contaminated soil: Many fungal species like microfungi can remediate the petroleum-contaminants from soil including Yeast, Penicillium, Arbuscular mycorrhiza, and Aspergillus species. The successful mycoremediation of many toxic environmental contaminants such as Petroleum hydrocarbons and oil spills in contaminated soil in different fungal species including *Fusarium, Candida, Aspergillus, Cephalosporium, Geotrichum, Cladosporium, Penicillium, Rhodotorula, Mucor and Trichoderma*. have been reported the successful remediation of petroleum fuel contaminated soil with fungi [58].

5.8 Mycoremediation of PCDD/Fs: Polychlorinated dibenzo-p-dioxins (PCDD/Fs) are toxic compounds and chemically stable in structure, they are produced from pesticides and herbicide manufacturing industries, pulp and paper chlorine bleaching, and incineration process of municipal waste as by-products [59]. These compounds consist of two aromatic rings with one to eight chlorine atoms, so they are less biodegradable. PCDD/Fs have a high hydrophobic character so they are capable of adsorbing with soil particles and soil organic matter. Different white rot fungi (WRF) can biodegrade these toxic PCDD/Fs efficiently [60, 61]

5.9 Xenobiotic mycoremediation/ Most soil contamination is caused by recalcitrant xenobiotics, and mycoremediation is the best way to remove them. Xenobiotics include alkanes, dioxins, fuels, PAHs, polychlorinated biphenyls, polyaromatic compounds, solvents, and synthetic azo dyes that degrade. Enzymes from Aspergillus sp., Phanerochaete chrysosporium, and Penicillium sp. can remove xenobiotics. Oxygenase enzyme from fungi breaks amide, ester, ether, aliphatic, and cyclic bonds in aromatic chemicals. Anthropogenic activities produce many xenobiotic and harmful contaminants in soil, including endocrine-disrupting chemicals (EDCs) and pharmaceutical personal care products (PPCPs), which have adverse effects on organisms, especially endogenous hormones [60, 62]. Rodarte-Morales ligninolytic fungi decompose EDCs and PPCPs. Many white rot fungi, such as Phanaerochaete chrysosporium and Polyporus sp., can bioremediate and completely remove toxic soil pollutants like atrazine herbicides, PAHs, petroleum hydrocarbons, PCBs, and pesticides. Polychlorinated biphenyl can be converted into nontoxic by Pleurotus ostreatus fungi. Chlorobenzoic acids (CBAs), produced by PCB reactivity, can be reduced by ligninolytic fungus. In contaminated soil, some fungal mycelia decompose PCB, PAH, and PCDD/F. Different fungal species mycoremediate soil pollutants. Different fungus. White rot fungi biodegrade pesticides, insecticides, herbicides, coal tars, fuels, and pentachlorophenol into carbon dioxide and water. According to many studies, fungi can bioremediate radioactive polluted environments by mineralizing uranium oxides and hydrocarbons. Numerous studies have examined the importance of soil fungi, saprotrophic basidiomycetes, and white rot fungi in bioremediating aromatic and petroleum-contaminated hydrocarbons [61, 63].

6. Recent applications of mycoremediation in sustainable agriculture

Agriculture is an important part of our life in terms of food, but various contaminants of soil affect the property of agricultural land and ultimately the crop's productivity [63]. The soil contaminants in agriculture are pesticides and their residues, fossil fuel and its combustion products, heavy metals and xenobiotics, etc. These recalcitrant chemicals are persistent in soil and less degradable [64]. The Arbuscular mycorrhizal fungus (AMF) is a well-known soil microorganism that creates a symbiotic association with vascular plant roots and increases the surface area of the root surface to adsorb nutrients and also facilitate supply of nitrogen and phosphorus to plants. Arbuscular mycorrhiza play a specific role in the supply of nutrients to plants and protect against various environmental stresses such as water stress and metal toxicity to adapt and survive in harsh conditions [65-69]

7. Enzymatic action of fungus in mycoremediation

Mycoremediation is a process that utilizes fungi to degrade or transform contaminants in the environment. Fungi possess various enzymatic capabilities that enable them to break down complex organic molecules into simpler forms [70]. These enzymes play a crucial role in the mycoremediation process by facilitating the degradation of contaminants. Some of the key enzymatic actions involved in mycoremediation include:

1. **Ligninolytic Enzymes**: Fungi such as white rot fungi produce ligninolytic enzymes like lignin peroxidase, manganese peroxidase, and laccase [71]. These enzymes are capable of breaking down lignin, a complex polymer found in wood and other plant materials. By breaking down lignin, these enzymes can also degrade various organic pollutants, including polycyclic aromatic hydrocarbons (PAHs), pesticides, and dyes [72].

2. **Cellulolytic Enzymes**: Cellulose-degrading enzymes like cellulase are produced by many fungi. These enzymes hydrolyze cellulose, the main component of plant cell walls, into simpler sugars such as glucose [73]. Cellulolytic enzymes are essential for fungi to access carbon sources in the environment, but they can also contribute to the degradation of cellulose-based pollutants [74].

3. **Proteolytic Enzymes**: Proteases are enzymes that break down proteins into smaller peptides or amino acids [75]. Fungi produce various proteases, which play a role in nutrient acquisition and metabolism. In mycoremediation, proteolytic enzymes can degrade organic pollutants such as animal waste, proteins in industrial effluents, and certain pesticides [76].

4. **Cytochrome P450 Monooxygenases**: These enzymes are involved in the oxidation of organic compounds [77]. Fungi possess cytochrome P450 monooxygenases that can oxidize a wide range of substrates, including environmental pollutants like polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and pesticides [78]. By oxidizing these compounds, fungi can initiate their breakdown and detoxification.

5. **Phytase**: Some fungi produce phytase, an enzyme that breaks down phytate, the principal storage form of phosphorus in plant seeds [79]. Phytase can enhance the

availability of phosphorus in the soil, promoting plant growth and aiding in the remediation of contaminated environments [80].

6. **Amylase**: Fungi also produce enzymes like amylase, which catalyze the hydrolysis of starch into simpler sugars [81]. While not directly involved in pollutant degradation, amylase production by fungi can contribute to the breakdown of organic matter in the environment, potentially affecting the availability of nutrients and influencing microbial communities involved in remediation processes [82].

Overall, the enzymatic action of fungi in mycoremediation is diverse and depends on the specific contaminants present in the environment as well as the metabolic capabilities of the fungal species involved [83]. By harnessing these enzymatic activities, mycoremediation offers a promising approach for the bioremediation of various environmental pollutants [84].

Certainly! Here's a table summarizing the key enzymatic actions of fungi involved in mycoremediation:

Enzyme Type	**Function**	**Examples of Contaminants Targeted**
Ligninolytic Enzymes	Break down lignin and related compounds	Polycyclic aromatic hydrocarbons (PAHs), pesticides, dyes
Cellulolytic Enzymes	Hydrolyze cellulose	Cellulose-based pollutants, plant material
Proteolytic Enzymes	Break down proteins	Animal waste, industrial effluents, certain pesticides
Cytochrome P450 Monooxygenases	Oxidize organic compounds	Polychlorinated biphenyls (PCBs), PAHs, pesticides
Phytase	Break down phytate	Phosphorus-containing pollutants, enhancing nutrient availability
Amylase	Hydrolyze starch	Organic matter decomposition, influencing nutrient availability

This table provides a concise overview of the enzymatic actions of fungi in mycoremediation, along with examples of contaminants targeted by each enzyme type.

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Enzyme Type	Function	Examples of Contaminants Targeted	Fungal Species Examples
Ligninolytic Enzymes	Break down lignin and related compounds	Polycyclic aromatic hydrocarbons (PAHs), pesticides, dyes	White rot fungi (e.g., *Phanerochaete chrysosporium*, *Pleurotus ostreatus*)
Cellulolytic Enzymes	Hydrolyze cellulose	Cellulose-based pollutants, plant material	Various fungi, including *Trichoderma reesei*, *Aspergillus niger*
Proteolytic Enzymes	Break down proteins	Animal waste, industrial effluents, certain pesticides	Various fungi, such as *Aspergillus niger*, *Aspergillus oryzae*
Cytochrome P450 Monooxygenases	Oxidize organic compounds	Polychlorinated biphenyls (PCBs), PAHs, pesticides	Various fungi, including *Pleurotus ostreatus*, *Aspergillus niger*
Phytase	Break down phytate	Phosphorus-containing pollutants, enhancing nutrient availability	*Aspergillus niger*, *Penicillium spp.*, *Trichoderma spp.*
Amylase	Hydrolyze starch	Organic matter decomposition, influencing nutrient availability	Various fungi, including *Aspergillus oryzae*, *Rhizopus spp.*, *Aspergillus niger*

This expanded table includes examples of fungal species known for their enzymatic capabilities in mycoremediation, providing a more comprehensive view of the enzymes involved and their applications in degrading specific contaminant

8. Conclusions

At present, many anthropogenic and industrial activities are increasing day by day and the various environmental toxic pollutants like organic, inorganic, and metallic pollutants produced from different sectors are released into the soil, which adversely affects living organisms. The remediation and removal of these toxicants are not possible naturally, so their dissociation is very necessary with some biologically efficient, environment-friendly, and cost-effective methods. Different species of fungi play an important role in converting many toxic pollutants into nontoxic forms with their mycelia as well as extracellular enzymes. However, more research efforts on this emerging and eco-friendly approach need to be enhanced. Further studies should be targeted on the identification of capable species of fungi that can efficiently remediate soil contaminants and tolerate stress conditions. Moreover, to remediate and treat the contaminated soil, further acceptance and application of this advanced technique is required in multidisciplinary fields.

References

1. Li, S., Wang, S., Wu, Q., Zhang, Y., Ouyang, D., Zheng, H., ... & Hao, J. (2023). Emission trends of air and CO 2 in China from 2005 to 2021. *Earth System Science Data Discussions*, *2023*, 1-22.

2. Shetty, S. S., Sonkusare, S., Naik, P. B., & Madhyastha, H. (2023). Environmental pollutants and their effects on human health. *Heliyon*.

3. Kordbacheh, F., & Heidari, G. (2023). Water pollutants and approaches for their removal. *Materials Chemistry Horizons*, *2*(2), 139-153.

4. Liu, Y., Yang, X., Tan, J., & Li, M. (2023). Concentration prediction and spatial origin analysis of criteria air pollutants in Shanghai. *Environmental Pollution*, *327*, 121535.

5. Coccia, M., & Bontempi, E. (pollutants 2023). New trajectories of technologies for the removal of pollutants and emerging contaminants in the environment. *Environmental Research*, *229*, 115938.

6. Wang, C., Liu, X., Yang, T., Sridhar, D., Algadi, H., Xu, B. B., ... & Guo, Z. (2023). An overview of metal-organic frameworks and their magnetic composites for the removal of pollutants. *Separation and Purification Technology*, 124144.

7. Thanigaivel, S., Vinayagam, S., Gnanasekaran, L., Suresh, R., Soto-Moscoso, M., & Chen, W. H. (2023). Environmental fate of aquatic pollutants and their mitigation by phycoremediation for the clean and sustainable environment: A review. *Environmental Research*, 117460.

8. Mehdizadeh, P., Jamdar, M., Mahdi, M. A., Abdulsahib, W. K., Jasim, L. S., Yousefi, S. R., & Salavati-Niasari, M. (2023). Rapid microwave fabrication of new nanocomposites based on Tb-Co-O nanostructures and their application as photocatalysts under UV/Visible light for removal of organic pollutants in water. *Arabian Journal of Chemistry*, *16*(4), 104579.

9. Sethi, N., Bhardwaj, P., Kumar, S., & Dilbaghi, N. (2019). Development and Evaluation of Ursolic Acid Co-Delivered Tamoxifen Loaded Dammar Gum Nanoparticles to Combat Cancer. *Advanced Science, Engineering and Medicine*, *11*(11), 1115-1124.

10. Sethi, N., Bhardwaj, P., Kumar, S., & Dilbaghi, N. (2019). Development And Evaluation Of Ursolic Acid Loaded Eudragit-E Nanocarrier For Cancer Therapy. *International Journal of Pharmaceutical Research (09752366)*, *11*(2).

11. Saini, A., Budania, L. S., Berwal, A., & Sethi, S. K. N. (2023). Screening of the Anticancer Potential of Lycopene-Loaded Nanoliposomes. *Tuijin Jishu/Journal of Propulsion Technology*, *44*(4), 1372-1383.

12. Zhao, Y., Tao, S., Liu, S., Hu, T., Zheng, K., Shen, M., & Meng, G. (2023). Research advances on impacts micro/nanoplastics and their carried pollutants on algae in aquatic ecosystems: A review. *Aquatic Toxicology*, 106725.

13. Herrera-Domínguez, M., Morales-Luna, G., Mahlknecht, J., Cheng, Q., Aguilar-Hernández, I., & Ornelas-Soto, N. (2023). Optical biosensors and their applications for the detection of water pollutants. *Biosensors*, *13*(3), 370.

14. Liu, C. J., Deng, S. G., Hu, C. Y., Gao, P., Khan, E., Yu, C. P., & Ma, L. Q. (2023). Applications of bioremediation and phytoremediation in contaminated soils and waters: CREST publications during 2018–2022. *Critical Reviews in Environmental Science and Technology*, *53*(6), 723-732.

15. Muter, O. (2023). Current trends in bioaugmentation tools for bioremediation: A critical review of advances and knowledge gaps. *Microorganisms*, *11*(3), 710.

16. Ayilara, M. S., & Babalola, O. O. (2023). Bioremediation of environmental wastes: the role of microorganisms. *Frontiers in Agronomy*, *5*, 1183691.

17. Dubey, S., Chen, C. W., Haldar, D., Tambat, V. S., Kumar, P., Tiwari, A., ... & Patel, A. K. (2023). Advancement in algal bioremediation for organic,

inorganic, and emerging pollutants. *Environmental Pollution*, *317*, 120840.

18. Narayanan, M., Ali, S. S., & El-Sheekh, M. (2023). A comprehensive review on the potential of microbial enzymes in multipollutant bioremediation: Mechanisms, challenges, and future prospects. *Journal of Environmental Management*, *334*, 117532.

19. Ambaye, T. G., Vaccari, M., Franzetti, A., Prasad, S., Formicola, F., Rosatelli, A., ... & Rtimi, S. (2023). Microbial electrochemical bioremediation of petroleum hydrocarbons (PHCs) pollution: Recent advances and outlook. *Chemical Engineering Journal*, *452*, 139372.

20. Kaura, S., Parle, M., Insa, R., Yadav, B. S., & Sethi, N. (2022). Neuroprotective effect of goat milk. *Small Ruminant Research*, *214*, 106748.

21. Poonam, D., Sethi, N., Pal, M., Kaura, S., & Parle, M. (2014). Optimization of shoot multiplication media for micro propagation of Withania somnifera: an endangered medicinal plant. *Journal of Pharmaceutical and Scientific Innovation (JPSI)*, *3*(4), 340-343.

22. Suman, J., Neeraj, S., Rahul, J., & Sushila, K. (2014). Microbial synthesis of silver nanoparticles by Actinotalea sp. MTCC 10637. *American Journal of Phytomedicine and Clinical Therapeutics*, *2*, 1016-23.

23. Milind, P., Sushila, K., & Neeraj, S. (2013). Understanding gout beyond doubt. *International Research Journal of Pharmacy*, *4*(9), 25-34.

24. Sethi, N., Kaura, S., Dilbaghi, N., Parle, M., & Pal, M. (2014). Garlic: A pungent wonder from nature. *International research journal of pharmacy*, *5*(7), 523-529.

25. Atuchin, V. V., Asyakina, L. K., Serazetdinova, Y. R., Frolova, A. S., Velichkovich, N. S., & Prosekov, A. Y. (2023). Microorganisms for bioremediation of soils contaminated with heavy metals. *Microorganisms*, *11*(4), 864.

26. Thacharodi, A., Hassan, S., Singh, T., Mandal, R., Khan, H. A., Hussain, M. A., & Pugazhendhi, A. (2023). Bioremediation of polycyclic aromatic hydrocarbons: An updated microbiological review. *Chemosphere*, 138498.

27. Ahmad, A., Mustafa, G., Rana, A., & Zia, A. R. (2023). Improvements in Bioremediation Agents and Their Modified Strains in Mediating Environmental Pollution. *Current Microbiology*, *80*(6), 208.

28. Milind, P., Bansal, N., & Kaura, S. (2014). Take soybean to remain evergreen. *International Research Journal of Pharmacy*, *5*(1), 1-6.

29. Parle, M., Malik, J., & Kaura, S. (2013). Life style related health hazards. *Int. Res. J. Pharm*, *4*(11), 1-5.

30. Parle, M., & Kaura, S. (2013). Green chilli: A memory booster from nature. *Ann. Pharm. and Pharm. Sci*, *4*(1), 17-21.

31. Kaura, S., & Parle, M. (2017). Evaluation of nootropic potential of green peas in mice. *Journal of Applied Pharmaceutical Science*, *7*(5), 166-173.

32. Kanungo, J., Sahoo, T., Bal, M., & Behera, I. D. (2023). Performance of bioremediation strategy in waste lubricating oil pollutants: a review. *Geomicrobiology Journal*, 1-14.

33. Yang, Q., Guo, Y., Xiang, Y., Chen, L., Liu, G., Liu, Y., ... & Jiang, G. (2023). Toward efficient bioremediation of methylmercury in sediment using merB overexpressed Escherichia coli. *Water Research*, *229*, 119502.

34. Saravanan, A., Kumar, P. S., Duc, P. A., & Rangasamy, G. (2023). Strategies for microbial bioremediation of environmental pollutants from industrial wastewater: A sustainable approach. *Chemosphere*, *313*, 137323.

35. Mishra, P., Kiran, N. S., Ferreira, L. F. R., Yadav, K. K., & Mulla, S. I. (2023). New insights into the bioremediation of petroleum contaminants: a systematic review. *Chemosphere*, 138391.

36. Dash, D. M., & Osborne, W. J. (2023). A systematic review on the implementation of advanced and evolutionary biotechnological tools for efficient bioremediation of organophosphorus pesticides. *Chemosphere*, *313*, 137506.

37. Paul, A., Dey, S., Ram, D. K., & Das, A. P. (2023). Hexavalent chromium pollution and its sustainable management through bioremediation. *Geomicrobiology Journal*, 1-11.

38. JEYAKUMAR, P., DEBNATH, C., Vijayaraghavan, R., & MUTHURAJ, M. (2023). Trends in bioremediation of heavy metal contaminations. *Environmental Engineering Research*, *28*(4).

39. Melo, N., Araújo, S. P., de Paula Queiroz Kraus, S., Lomheim, L., Quintero, P. B., Mack, E. E., ... &

Gavazza, S. (2023). Strategies for bioremediation of soil from an industrial site exposed to chlorinated and nitroaromatic compounds. *Groundwater Monitoring & Remediation*, *43*(3), 108-120.

40. Zhou, X., Zhang, S., Wang, R., An, Z., Sun, F., Shen, C., ... & Su, X. (2023). A novel strategy for enhancing bioremediation of polychlorinated biphenyl-contaminated soil with resuscitation promoting factor and resuscitated strain. *Journal of Hazardous Materials*, *447*, 130781.

41. Kaura, S., & Parle, M. (2017). Anti-ageing activity of moong bean sprouts. *International Journal of Pharmaceutical Sciences and Research*, *8*(10), 4318-4324.

42. Meenakshi, P., Neeraj, S., Sushila, K., & Milind, P. (2014). Plant regeneration studies in Safed musli (Chlorophytum sp.). *Int J Res Ayuveda Pharm*, *5*, 195-98.

43. Kumara, U. A., Jayaprada, N. V. T., & Thiruchchelvan, N. (2023). Bioremediation of Polluted Water. In *Current Status of Fresh Water Microbiology* (pp. 321-346). Singapore: Springer Nature Singapore.

44. Wang, S., Cheng, F., & Guo, S. (2023). Highly efficient screening and optimal combination of functional isolates for bioremediation of hydrocarbon-polluted soil. *Environmental Research*, *219*, 115064.

45. Demarco, C. F., Quadro, M. S., Selau Carlos, F., Pieniz, S., Morselli, L. B. G. A., & Andreazza, R. (2023). Bioremediation of aquatic environments contaminated with heavy metals: A review of mechanisms, solutions and perspectives. *Sustainability*, *15*(2), 1411.

46. Funtikova, T. V., Akhmetov, L. I., Puntus, I. F., Mikhailov, P. A., Appazov, N. O., Narmanova, R. A., ... & Solyanikova, I. P. (2023). Bioremediation of Oil-Contaminated Soil of the Republic of Kazakhstan Using a New Biopreparation. *Microorganisms*, *11*(2), 522.

47. Wróbel, M., Śliwakowski, W., Kowalczyk, P., Kramkowski, K., & Dobrzyński, J. (2023). Bioremediation of heavy metals by the genus Bacillus. *International Journal of Environmental Research and Public Health*, *20*(6), 4964.

48. Kashem, A. H. M., Das, P., AbdulQuadir, M., Khan, S., Thaher, M. I., Alghasal, G., ... & Al-Jabri, H. (2023). Microalgal bioremediation of brackish aquaculture wastewater. *Science of The Total Environment*, *873*, 162384.

49. Tambat, V. S., Tseng, Y. S., Kumar, P., Chen, C. W., Singhania, R. R., Chang, J. S., ... & Patel, A. K. (2023). Effective and sustainable bioremediation of molybdenum pollutants from wastewaters by potential microalgae. *Environmental Technology & Innovation*, *30*, 103091.

50. Nicula, N. O., Lungulescu, E. M., Rîmbu, G. A., Marinescu, V., Corbu, V. M., & Csutak, O. (2023). Bioremediation of Wastewater Using Yeast Strains: An Assessment of Contaminant Removal Efficiency. *International Journal of Environmental Research and Public Health*, *20*(6), 4795.

51. Ling, H., Hou, J., Du, M., Zhang, Y., Liu, W., Christie, P., & Luo, Y. (2023). Surfactant-enhanced bioremediation of petroleum-contaminated soil and microbial community response: A field study. *Chemosphere*, *322*, 138225.

52. Xu, G., Zhao, S., Liu, J., & He, J. (2023). Bioremediation of organohalide pollutants: progress, microbial ecology, and emerging computational tools. *Current Opinion in Environmental Science & Health*, *32*, 100452.

53. Yang, Y., Zhang, W., Zhang, Z., Yang, T., Xu, Z., Zhang, C., ... & Lu, W. (2023). Efficient bioremediation of petroleum-contaminated soil by immobilized bacterial agent of Gordonia alkanivorans W33. *Bioengineering*, *10*(5), 561.

54. Kumar, K., & Singh, D. (2023). Toxicity and bioremediation of the lead: a critical review. *International Journal of Environmental Health Research*, 1-31.

55. Williamson, A. J., Binet, M., & Sergeant, C. (2023). Radionuclide biogeochemistry: from bioremediation toward the treatment of aqueous radioactive effluents. *Critical Reviews in Biotechnology*, 1-19.

56. Vulpe, C. B., Matica, M. A., Kovačević, R., Dascalu, D., Stevanovic, Z., Isvoran, A., ... & Menghiu, G. (2023). Copper accumulation efficiency in different recombinant microorganism strains available for bioremediation of heavy metal-polluted waters. *International Journal of Molecular Sciences*, *24*(8), 7575.

57. Liu, Q., Wang, Y., Sun, S., Tang, F., Chen, H., Chen, S., ... & Li, L. (2023). A novel chitosan-biochar immobilized microorganism strategy to enhance bioremediation of crude oil in soil. *Chemosphere*, *313*, 137367.

58. Ghosh, D., Ghorai, P., Sarkar, S., Maiti, K. S., Hansda, S. R., & Das, P. (2023). Microbial assemblage for solid waste bioremediation and valorization with an essence

of bioengineering. *Environmental Science and Pollution Research*, *30*(7), 16797-16816.

59. Jalali, F. M., Chahkandi, B., Gheibi, M., Eftekhari, M., Behzadian, K., & Campos, L. C. (2023). Developing a smart and clean technology for bioremediation of antibiotic contamination in arable lands. *Sustainable Chemistry and Pharmacy*, *33*, 101127.

60. Hidangmayum, A., Debnath, A., Guru, A., Singh, B. N., Upadhyay, S. K., & Dwivedi, P. (2023). Mechanistic and recent updates in nano-bioremediation for developing green technology to alleviate agricultural contaminants. *International Journal of Environmental Science and Technology*, *20*(10), 11693-11718.

61. Tambat, V. S., Patel, A. K., Chen, C. W., Raj, T., Chang, J. S., Singhania, R. R., & Dong, C. D. (2023). A sustainable vanadium bioremediation strategy from aqueous media by two potential green microalgae. *Environmental Pollution*, *323*, 121247.

62. Satya, A. D. M., Cheah, W. Y., Yazdi, S. K., Cheng, Y. S., Khoo, K. S., Vo, D. V. N., ... & Show, P. L. (2023). Progress on microalgae cultivation in wastewater for bioremediation and circular bioeconomy. *Environmental research*, *218*, 114948.

63. Anekwe, I. M. S., & Isa, Y. M. (2023). Bioremediation of acid mine drainage–Review. *Alexandria Engineering Journal*, *65*, 1047-1075.

64. Anekwe, I. M. S., & Isa, Y. M. (2023). Bioremediation of acid mine drainage–Review. *Alexandria Engineering Journal*, *65*, 1047-1075.

65. Ma, B., Song, W., Zhang, X., Chen, M., Li, J., Yang, X., & Zhang, L. (2023). Potential application of novel cadmium-tolerant bacteria in bioremediation of Cd-contaminated soil. *Ecotoxicology and Environmental Safety*, *255*, 114766.

66. Hlihor, R. M., & Cozma, P. (2023). Microbial Bioremediation of Environmental Pollution. *Processes*, *11*(5), 1543.

67. Cui, C., Shen, J., Zhu, Y., Chen, X., Liu, S., & Yang, J. (2023). Bioremediation of phenanthrene in saline-alkali soil by biochar-immobilized moderately halophilic bacteria combined with Suaeda salsa L. *Science of the Total Environment*, *880*, 163279.

68. Anand, S., & Padmanabhan, P. (2023). Bioremediation: The Remedy to Expanding Pollution. In *Modern Approaches in Waste Bioremediation: Environmental Microbiology* (pp. 13-28). Cham: Springer International Publishing.

69. Xia, M., Chen, B., Fan, G., Weng, S., Qiu, R., Hong, Z., & Yan, Z. (2023). The shifting research landscape for PAH bioremediation in water environment: a bibliometric analysis on three decades of development. *Environmental Science and Pollution Research*, *30*(27), 69711-69726.

70. Akpasi, S. O., Anekwe, I. M. S., Tetteh, E. K., Amune, U. O., Shoyiga, H. O., Mahlangu, T. P., & Kiambi, S. L. (2023). Mycoremediation as a potentially promising technology: current status and prospects—a review. *Applied Sciences*, *13*(8), 4978.

70. Negi, B. B., & Das, C. (2023). Mycoremediation of wastewater, challenges, and current status: A review. *Bioresource Technology Reports*, 101409.

71. Navina, B. K., Velmurugan, N. K., Kumar, P. S., Rangasamy, G., Palanivelu, J., Thamarai, P., ... & Shakoor, A. (2024). Fungal bioremediation approaches for the removal of toxic pollutants: Mechanistic understanding for biorefinery applications. *Chemosphere*, *350*, 141123.

73 Siddharthan, S., Thangaraj, S., Paulraj, S., RajaMohmed, B., Rakkamuthu, K., Dharmaraj, V., ... & Umadevi, P. (2023). Myco-remediation of selenium contaminated environment and future prospects: An overview. *Environmental Quality Management*.

74 Ray, M. K., Panda, J., Panda, B. P., Mohanta, T. K., & Mohanta, Y. K. (2023). Mycoremediation of Heavy Metals and/or Metalloids in Soil. In *Land Remediation and Management: Bioengineering Strategies* (pp. 161-190). Singapore: Springer Nature Singapore.

75 Vaksmaa, A., Guerrero-Cruz, S., Ghosh, P., Zeghal, E., Hernando-Morales, V., & Niemann, H. (2023). Role of fungi in bioremediation of emerging pollutants. *Frontiers in Marine Science*, *10*, 1070905.
76 Shelke, D. B., Sonawane, H., Chambhare, M. R., Madne, M., Shinde, B., & Math, S. (2023). Fungal Enzymes in Bioremediation of Environmental Pollutants. In *Land Remediation and Management: Bioengineering Strategies* (pp. 147-160). Singapore: Springer Nature Singapore.

77 Mohamadhasani, F., & Rahimi, M. (2022). Growth response and mycoremediation of heavy metals by

fungus Pleurotus sp. *Scientific Reports*, *12*(1), 19947.

78 Goligar, N., Saadatmand, S., & Khavarinejad, R. A. (2023). Mycoremediation of lead and cadmium by lignocellulosic enzymes of Pleurotus eryngii. *AMB Express*, *13*(1), 127

79 Bokade, P., & Bajaj, A. (2023). Molecular advances in mycoremediation of polycyclic aromatic hydrocarbons: Exploring fungal bacterial interactions. *Journal of Basic Microbiology*, *63*(3-4), 239-256.

80 Barman, S., Chowdhury, R., & Bhattacharya, S. S. (2023). Fungal-Based Land Remediation. In *Bio-Inspired Land Remediation* (pp. 165-188). Cham: Springer International Publishing.

81 Chaurasia, P. K., Nagraj, Sharma, N., Kumari, S., Yadav, M., Singh, S., ... & Bharati, S. L. (2023). Fungal assisted bio-treatment of environmental pollutants with comprehensive emphasis on noxious heavy metals: Recent updates. *Biotechnology and Bioengineering*, *120*(1), 57-81.

82 Khatua, S., Simal-Gandara, J., & Acharya, K. (2023). Myco-remediation of plastic pollution: current knowledge and future prospects. *Biodegradation*, 1-31.

83 Antón-Herrero, R., Chicca, I., García-Delgado, C., Crognale, S., Lelli, D., Gargarello, R. M., ... & D'Annibale, A. (2023). Main Factors Determining the Scale-Up Effectiveness of Mycoremediation for the Decontamination of Aliphatic Hydrocarbons in Soil. *Journal of Fungi*, *9*(12), 1205.

84 Bibbins-Martínez, M., Juárez-Hernández, J., López-Domínguez, J. Y., Nava-Galicia, S. B., Martínez-Tozcano, L. J., Juárez-Atonal', R., ... & Díaz-Godinez, G. (2023). Potential application of fungal biosorption and/or bioaccumulation for the bioremediation of wastewater contamination: A review. *Journal of Environmental Biology*, *44*(2), 135-145.