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Fungal bioremediation: An overview of the mechanisms, applications and future perspectives

Yuvaraj Dinakarkumar [a], Gnanasekaran Ramakrishnan [b], Koteswara Reddy Gujjula [b,*], Vishali Vasu [a], Priyadharishini Balamurugan [a], Gayathri Murali [a]

[a] Department of Biotechnology, Vel Tech High Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Avadi, Chennai 600 062,Tamil Nadu, India
[b] Department of Biotechnology, Koneru Lakshmaiah Education Foundation (Deemed to be University), Vaddeswram, Green Fields 522502, AP, India

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A B S T R A C T

Fungal bioremediation represents a promising and sustainable approach to addressing environmental pollution by exploiting the natural metabolic capabilities of fungi to degrade and detoxify a wide array of pollutants. This review provides a comprehensive overview of the mechanisms, applications, and future perspectives of fungal bioremediation. Fungi are uniquely equipped with an extensive arsenal of enzymes, including laccases, peroxidases, and hydrolases, which facilitate the breakdown of complex organic compounds, heavy metals, and xenobiotics into less harmful substances. The versatility of fungi enables their application across various environmental contexts, including soil, water, and air remediation. The efficacy of fungal bioremediation is demonstrated in its ability to degrade persistent organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and petroleum hydrocarbons, as well as to immobilize and transform heavy metals through biosorption and bioaccumulation. This review also discusses the challenges and limitations associated with fungal bioremediation, such as the need for optimized environmental conditions and potential ecological impacts. Future research directions are highlighted, including the integration of omics technologies for the elucidation of fungal metabolic pathways and the development of biotechnological innovations to scale up fungal bioremediation processes. This review underscores the critical role of fungi in environmental remediation and emphasizes the need for continued research and technological advancements to harness their full potential in addressing global environmental challenges.

1. Introduction

The intricate process of microbial remediation of metals is influenced by factors including pH, temperature, time, ionic strength, and metal concentration [1]. Unlike organic pollutants, metals are not subject to biological degradation and thus can persist in soil for millennia. Instead, metals remain in soil through transformations between different oxidation states or organic complexes. Aqueous metal ions can be sequestered by microorganisms, a process termed “biosorption” [2].

Microorganisms play a crucial role in detoxifying environments and soils. Mycoremediation, a promising technology, utilizes fungi to degrade or transform harmful substances into less toxic or non-toxic forms. Various fungal species, including Pleurotus ostreatus, Rhizopus arrhizus, Phanerochaete chrysosporium, Phanerochaete sordida, Trametes hirsuta, Trametes versicolor, Lentinus tigrinus, and Lentinus edodes, are employed as mycoremediators [3]. Mycoremediation can be applied in two main ways: *in situ* and *ex situ*. *In situ* techniques address the contaminated soil directly at the site, whereas *ex situ* methods involve the excavation of contaminated soil for subsequent bioremediation [4]. Current waste disposal and treatment techniques often fall short in adequately addressing issues of soil depletion and environmental degradation. Thus, finding alternative methods for pollutant removal is crucial for promoting sustainable development [5]. Mycoremediation is recommended as an efficient approach to detoxifying contaminated soil and environments with reduced chemical, resource, and time inputs [6]. However, further research is required to explore fungi’s potential as mycoremediators to achieve agricultural sustainability [7]. Bioremediation, including mycoremediation, leverages the metabolic capabilities of microorganisms to transform environmental pollutants into less hazardous or nonhazardous forms, making it an attractive technology with minimal chemical and energy input [8]. Over the past two decades, numerous mycologists have investigated various

* Corresponding author.
E-mail address: koteswarareddy@kluniversity.in (K.R. Gujjula).

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fungal species for their potential to degrade organic compounds. The discovery of the white rot fungus Phanerochaete chrysosporium has significantly advanced mycoremediation research worldwide. "Mycoremediation" combines "myco" (fungus) and "remediation" (to clean, resolve, or correct) and involves using fungi, particularly mushrooms, to produce low-tech biomass capable of effectively degrading industrial and environmental pollutants [9]. The mycelium targets and breaks down organic pollutants, functioning as a self-healing filter [10]. Studies have demonstrated the efficacy of fungi in degrading pollutants such as polycyclic aromatic hydrocarbons, PCBs, and oil spills [11].

2. Fungal bioremediation

2.1. Basic principles of bioremediation

Bioremediation is a creative and optimistic technology that can be utilized to remove and reduce heavy metals from polluted water and lands [12].Bioremediation is recognized as the most basic and reliable way of eliminating pollutants, particularly petroleum and its refractory components, because it is based on the metabolic powers of microorganisms (Fig. 1). Microorganisms are an important part of heavy metal bioremediation[13].Using genetic engineering, organisms that might potentially reduce various forms of polycyclic hydrocarbons (PAHs) can be developed.

2.2. Mycoremediation

Mycoremediation is the process which utilizes fungi to eliminate poisons from various environmental components, either alive or dead [15].Mycoremediation is a cheap procedure that doesn't create any hazardous waste. The effectiveness of mycoremediation is dependent on the selection and use of an appropriate fungus species for the target heavy metal or other pollutant. This can be a viable and cost-effective answer to the growing problem of soil and water contamination [16]. Mycoremediation is a bioremediation process that uses fungi to eliminate harmful compounds; it can be performed in the presence of both filamentous fungi (molds) and macrofungi (mushrooms). As a result, mycoremediation can be used as a biological instrument for pollutant degradation, transformation, or immobilization [17].

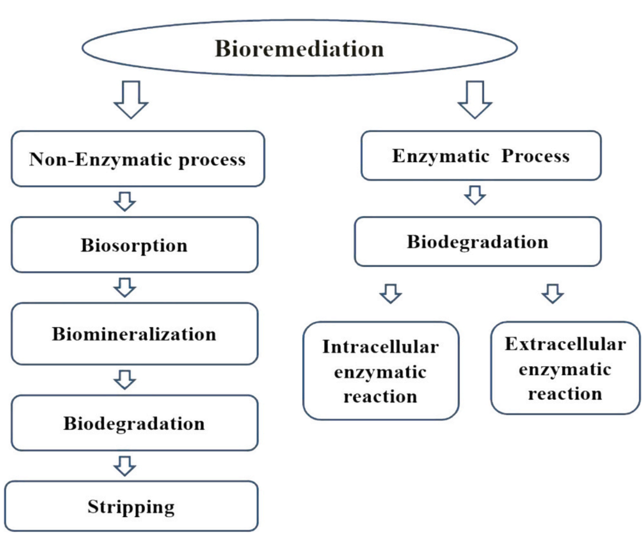

Fig. 1. Bioremediation mechanism [14].

3. Bioremediation of different pollutants using Fungi

3.1. Bioremediation of heavy metals

Fungi such as *Aspergillus niger* and *Trichoderma harzianum* are effective in the bioremediation of heavy metals due to their ability to secrete organic acids that chelate metals and facilitate their removal. *A. niger* produces citric acid, which can solubilize metals like cadmium and lead, converting them into less toxic forms that can be immobilized or precipitated out of the environment. For example, *A. niger* has been shown to reduce cadmium concentration by up to 87% within 14 days under laboratory conditions [18,19,20]. This process not only reduces the bioavailability and toxicity of the metals but also prevents their further migration in the environment. The ability of fungi to bind heavy metals on their cell walls through functional groups like carboxyl, amino, and hydroxyl groups also enhances their capacity for heavy metal detoxification [21].One of the unique advantages of fungi is their ability to form extensive mycelial networks, which facilitate the transport and distribution of nutrients and enzymes over large areas. This network allows fungi to penetrate deep into the soil and reach pollutants that are not accessible to bacteria. The mycelial network can also promote the co-metabolism of pollutants, where the degradation of one compound supports the breakdown of another. For example, in bioremediation of soil contaminated with a mixture of hydrocarbons and heavy metals, the mycelial network of fungi can simultaneously degrade organic pollutants and immobilize heavy metals, enhancing the overall remediation efficiency [22].

3.2. Bioremediation of hydrocarbons

Fungal species such as *Phanerochaete chrysosporium* and *Pleurotus ostreatus* play a crucial role in degrading hydrocarbons found in contaminated soils and waters. These fungi produce ligninolytic enzymes, including laccase and peroxidase, which break down complex hydrocarbons into simpler compounds. *P. chrysosporium* can degrade up to 95% of benzo[*a*]pyrene, a polycyclic aromatic hydrocarbon, within 30 days [23,24] . This degradation capability is significant compared to bacterial strains, which achieve lower degradation rates under similar conditions [25,26].This high degradation efficiency is attributed to the fungi's ability to produce non-specific extracellular enzymes that can attack a broad range of chemical bonds in these complex molecules [27].

3.3. Bioremediation of dyes

Fungi like *Trametes versicolor* and *Pleurotus ostreatus* are known for their ability to decolorize and degrade synthetic dyes through enzymatic action. Enzymes such as laccase and manganese peroxidase degrade the complex structures of dyes, making them non-toxic. For instance, *T. versicolor* can degrade 90% of Reactive Black 5 dye within 7 days [28,27].

Most fungi are terrestrial; however, others are predominantly or totally aquatic and survive in freshwater. A few marine fungi have also been identified. Most fungi, on the other hand, have terrestrial environments and live in soil or on dead plant materials. In nature, these fungi perform critical roles in the mineralization of organic carbon [29]. The terrestrial species include parasites and pathogens that affect humans and other animals, as well as free-living saprotrophs that live in dung and soil. Pathogenic aquatic fungus can be found [30].

Additionally significant factors in the biodegradation of some materials are fungi. Fungi are economically valuable because they provide antibiotics, vitamins, and various chemicals used in industry (such as alcohols, acetone, and enzymes), as well as because they participate in fermentation processes that result in the production of alcoholic beverages, vinegar, cheese, and bread dough, as well as single cell protein. They serve an important part in soil renewal by breaking down organic debris, which is an unwelcome function because it causes rotting of clothing and other goods and deterioration of food (Table 1).

4. Advantages of fungal bioremediation

Fungi offer several distinct advantages over bacteria in the bioremediation of pollutants due to their unique biological and ecological characteristics. These advantages make fungi particularly effective in treating a wide range of contaminants in diverse environmental conditions.

4.1. Adaptability to extreme conditions

Fungi are highly adaptable and can thrive in extreme pH, temperature, and moisture conditions where bacterial activity may be limited. For instance, fungi like *Aspergillus niger* and *Penicillium chrysogenum* can grow in highly acidic environments with pH as low as 2, and in alkaline environments with pH up to 11 [18]. This adaptability allows fungi to be effective in environments that are inhospitable to many bacteria, such as acidic mine drainage sites or alkaline industrial waste areas.

4.2. Enzymatic diversity and efficiency

Fungi possess a diverse range of enzymes that can degrade a wide variety of pollutants. These include ligninolytic enzymes like laccases, peroxidases, and oxidoreductases, which are capable of breaking down complex organic molecules. For example, white-rot fungi like Phanerochaete chrysosporium produce extracellular enzymes that can degrade lignin and a range of xenobiotic compounds, including polycyclic aromatic hydrocarbons (PAHs) and chlorinated phenols [23]. This enzymatic diversity allows fungi to degrade complex and recalcitrant pollutants that are resistant to bacterial degradation.

4.3. Versatility in bioremediation applications

Fungi are versatile and can be used in various bioremediation applications, including soil, water, and air decontamination. They are effective in both *in situ* and *ex situ* remediation strategies. *In situ* applications involve the direct treatment of contaminated sites, where fungi are introduced to degrade pollutants on site. *Ex situ* applications involve the removal of contaminated material to a controlled environment for treatment. For instance, fungi have been used successfully in bioreactors to treat wastewater contaminated with dyes and heavy metals, achieving significant reductions in pollutant concentrations [47].

4.4. Symbiotic relationships

Fungi often form symbiotic relationships with plants, which can further enhance bioremediation processes. Mycorrhizal fungi, for example, associate with plant roots and facilitate the uptake and translocation of nutrients, including degraded pollutants. This symbiosis not only supports the health and growth of plants in contaminated soils but also enhances the overall efficiency of the bioremediation process by extending the degradation capabilities of the fungi through the root network of the plants [48].

5. Mechanisms of fungal bioremediation

Microbes can be found in a wide variety of habitats. Fungi are among the many microorganisms that are very opportunistic, have a wide range of adaptability, and are quick to respond to stressful events, environmental disasters, and extreme climatic circumstances [49].They can break down toxic substances and complex hydrocarbon chains into less dangerous, biodegradable forms to aid in environmental cleanup. Numerous fungi also have a high ability to bind with metal ions, which includes metal ion outflow from the cell as well as the accumulation and formation of metal ion complexes within the cell. They can also transform harmful metal ions to a harmless state later. Several methods have arisen to immobilize, mobilize, convert, render inert, or tolerate the intake of heavy metal ions [50]. Fungal bioremediation involves several key reaction processes:

Table 1
Fungal species employed in organic chemical bioremediation.

Fungi	Organic chemicals /compounds	Sources of organic chemicals/compounds	References
Pleurotus ostreatus	Pesticide, heptachlor	Agriculture, soil, and surface runoff water	[31].
Aspergillus terreus	Chlorpyrifos	Treated agricultural fields	[32]
Trametes versicolor, Pleurotus ostreatus, white-rot fungi	PAH	Soil/sediments, coal, wood	[33].
Doratomycesverrucisporus, Phomaeupyrena,Myceliophthorathermophila, Doratomycesnanus, Doratomycesverrucisporus,Thermoascuscrustaceus, Aspergillus niger	POPs Polychlorinated biphenyls	Agrochemicals, Industrial chemicals	[34]
White-rot fungi, Penicillium sp.,Aspergillusniger, Pycnoporuscinnabarinus, Trichoderma sp., Ceriporiametamorphosa, Ganoderma sp., Bjerkanderaadusta, Aspergillus sojae	Textile dye decolorization	Textiles	[35]
Phanerochaetesordida, white-rot fungi	Polychlorinated dibenzofurans	Emission from volcanic, chemical industries, *etc.*	[36]
Rhizopus sp., Mucor sp., Candida sp., Penicillium sp., Aspergillus niger	Petroleum products, crude oil	Underground storage tanks	[37]
Pleurotus eryngii, white-rot fungi	Naphthalene	Cigarette smoke, car exhaust	[38]
Armillaria sp.	Anthracene	Vehicle exhaust, hazardous waste site	[39]
Aspergillus jegita, Aspergillus sp.,Aspergillus flavus, Aspergillus niger	Effluent from leather Tanning	Tannery wastewater	[40]
Rhizopus oryzae	Bleached kraft pulp mill effluent	Lime mud, pulp mill sludge	[41]
Phanerochaetechrysosporium, Bjerkanderaadusta	Citalopram, sulfamethoxazole, Fluoxetine	Pharmaceuticals	[42]
Rhizopus stolonifera, Gongronella sp.	Folpet, metalaxyl	Vineyard soil samples	[43]
Fusarium solani, Gliocladium roseum, Penicillium, Chrysosporium keratinophilum	Caffeine	Waste water	[44]
Exophialaxenobiotica	Gasoline	Crude oil, petroleum refineries	[45]
Aspergillus flavus, Curvularia, Asper-gillus, Pythyme	Heavy metals	oil refineries, petrochemical plants, pesticide production, chemical industry.	[46] [32]

5.1. Precipitation reactions

Fungi can induce precipitation reactions by converting soluble metal ions into insoluble forms. For instance, fungi can secrete organic acids that react with metal ions to form metal oxalates or phosphates, which precipitate out of solution. *Aspergillus niger* has been documented to facilitate the precipitation of lead as lead oxalate, effectively removing it from contaminated media [47] .

5.2. Enzymatic degradation

Fungi secrete a variety of enzymes, including laccase and manganese peroxidase, which can degrade complex organic pollutants. These enzymes break down the molecular structures of pollutants such as polycyclic aromatic hydrocarbons (PAHs) and synthetic dyes into simpler, less harmful compounds. For example, Phanerochaete chrysosporium secretes ligninolytic enzymes that degrade lignin and PAHs through oxidative cleavage, leading to significant reductions in pollutant concentrations [51,52] .

5.3. Biosorption and bioaccumulation

One of the primary mechanisms by which fungi remove heavy metals from contaminated environments is biosorption. Fungi have cell walls rich in functional groups such as carboxyl, hydroxyl, and amine groups, which can bind metal ions through ionic exchange, complexation, and chelation. For example, *Aspergillus niger* and *Penicillium chrysogenum* are known for their high biosorption capacity for metals like cadmium, lead, and mercury [53]. These metals are adsorbed onto the fungal cell surface, reducing their mobility and bioavailability in the environment.

Bioaccumulation, on the other hand, involves the uptake and internalization of metals into fungal cells, where they can be sequestered and stored in vacuoles or bound to intracellular proteins. *Trichoderma harzianum* can bioaccumulate significant amounts of copper and zinc, effectively removing these metals from contaminated soil [21].

5.4. Chelation and precipitation

Phosphate-solubilizing fungi, such as *Aspergillus niger*, secrete organic acids like citric acid and oxalic acid, which play a crucial role in chelation and precipitation of heavy metals. Citric acid can form stable complexes with metals such as lead, cadmium, and aluminum, reducing their bioavailability and toxicity. For instance, *A. niger* can produce up to 15 g/L of citric acid, which effectively chelates metals like cadmium, facilitating their immobilization and subsequent removal from the environment [20].

Oxalic acid secretion by fungi aids in the precipitation of metal oxalates, which are insoluble and can be easily removed from soils and water. The precipitation process involves the conversion of soluble metal ions into solid metal oxalates that can be separated through sedimentation or filtration. For example, *Aspergillus niger* has been shown to precipitate lead as lead oxalate, effectively reducing lead concentrations in contaminated water [54,55].

5.5. Enzymatic degradation

Fungi produce a wide array of extracellular enzymes that facilitate the degradation of complex organic pollutants. These enzymes include laccases, manganese peroxidases, and lignin peroxidases, which catalyze the oxidation of various pollutants. For instance, white-rot fungi like Phanerochaete chrysosporium secrete ligninolytic enzymes that degrade lignin and other complex organic molecules, including polycyclic aromatic hydrocarbons (PAHs) and synthetic dyes [23].

Laccases, for example, catalyze the oxidation of phenolic compounds, leading to the breakdown of complex organic molecules into smaller, less harmful compounds. This process is particularly effective in the degradation of persistent organic pollutants such as PAHs and PCBs, which are resistant to conventional degradation processes [52].

5.6. Redox reactions

Fungi are also capable of mediating redox reactions that play a critical role in the transformation and detoxification of pollutants. These reactions involve the transfer of electrons between the pollutant and the fungal cells, leading to the reduction or oxidation of the contaminant. For example, fungi can reduce hexavalent chromium (Cr(VI)), a highly toxic form of chromium, to trivalent chromium (Cr(III)), which is much less toxic and more easily removed from the environment. *Aspergillus niger* has been reported to reduce Cr(VI) to Cr(III) under both aerobic and anaerobic conditions, making it a potent agent for the bioremediation of chromium-contaminated sites [20].

5.7. Mycorrhizal associations

Fungi that form symbiotic associations with plants, such as mycorrhizal fungi, enhance the bioremediation process by improving the uptake and translocation of contaminants within the plant-fungal system. Mycorrhizal fungi extend the root system of plants, increasing the surface area for nutrient and pollutant absorption. These fungi can secrete organic acids and chelating agents that facilitate the uptake of metals and their subsequent stabilization within the plant tissues. For instance, arbuscular mycorrhizal fungi have been shown to improve the phytoremediation of heavy metals like arsenic and lead by enhancing their uptake and immobilization in plant roots [47].

5.8. Co-metabolism and synergistic interactions

Fungi can also engage in co-metabolism, where the degradation of one compound facilitates the breakdown of another. This process is particularly useful in environments contaminated with complex mixtures of pollutants. For example, fungi can degrade hydrocarbons while simultaneously enhancing the breakdown of heavy metals by altering the pH and redox conditions in the soil [51]. Moreover, fungi can interact synergistically with other microorganisms, such as bacteria, to enhance the overall bioremediation process. These interactions can lead to the sequential degradation of pollutants, where fungi break down complex molecules into simpler intermediates that are further degraded by bacteria.(Table 2).

6. Applications of Mycoremediation

6.1. Soil and land remediation

A subset of bioremediation known as mycoremediation uses fungi to breakdown, restore, and repair damaged habitats[61].In mycoremediation, fungi are used for bioremediation, and the long threads (hyphae) that grow from them adhere to soil, rocks, and plant roots to form a filamentous body that can withstand heavy metals and adjust to fluctuations in temperature, pH, and nutrition [62].Because of the unique qualities of their hyphal network, biomass, and protracted life cycle, fungi surpass bacteria in bioremediation of polluted environments [63].Natural bacteria compete with metal-resistant fungi in extreme environments[64].Fungi cell walls contain polysaccharides and proteins with metal-ion-binding amino, phosphate, hydroxyl, sulphate, and carboxyl groups[65].These functional groups offer the ligand atoms needed to form complexes with metal ions, which attract and retain metals in the biomass [66].The ability to evaluate the likelihood of metal removal is enabled by selecting metal-tolerant fungus from a polluted environment. A successful site-specific bioremediation technique is the bioaugmentation of fungi that may be able to bind metals. Numerous experts have also emphasized the importance of doing research on wild-type fungal strains to develop efficient bioremediation technologies

Table 2
Mechanisms of action of fungal enzymes on organic pollutants.

Enzymes	Fungi	Compound	Mechanisms of action	References
Manganese per-oxidase (MnP)	*Phanerochaetechry sosporium Ceriporiopsis subvermispora*	Di(2 ethylhexyl) phthalate, heavy metals, total petro-leum hydrocarbons, Polyaromatic hydro-carbon (PAH) Reactive black 5, veratryl alcohol	H_2O_2-driven single-electron oxidation of Mn_2p to Mn_3p, which further oxidizes organic compounds	[56]
Lignin peroxidases	*Phanerochaete chrysosporium Pleurotus pulmonarius Trametes versicolor, Trametes sp.*	Pyrene, Bentazon (herbicide), aminodinitrotoluenes,PAH Polyaromatic hydrocarbon Phencyclidine (PCP)	Single-electron oxida-tion using H_2O_2 on aromatic compounds	[57].
Lipase	*Trichoderma sp., Curvularia sp., Drechslera sp., Lasiodiplodia sp., Mucor sp., Fusarium sp., Aspergillus sp., Rhizopus sp. White-rot fungi, Basidiomycetes; Trametes versicolor, Phanerochaete chrysosporium,Pleurotus sp., Bjerkanderaadusta White-rot fungi, Bjerkanderaadusta, Ceriporia metamorphosa, Ganoderma sp.*	PAHs Organic pollutants, Pesticides Dye decolorization	Single-electron oxida-tion using H_2O_2 on aromatic compounds	[58]
Catalase	*Curvularia sp., Acremonium sp., Aspergillus sp., Pythyme sp., Aspergil-lus flavus*	Heavy metals	Single-electron oxida-tion using H_2O_2 on aromatic compounds	[17]
Laccase	*Bjerkanderaadusta, Phanerochaete chrysosporium, Trametes versicolor, Pleurotus sp. Doratomyces nanus, Thermoascus crustaceus, Phoma Eupyrena, Doratomyces verrucisporus, Myceliophthora thermophila, Doratomyces purpureofuscus Trametesvillosa, Myceliophthora thermophila, Pycnoporuscoccineus, Coriolopsis rigida Flexo Pleurotus Pulmonarius*	Pesticides PCB Flexographic inks Di(2-ethylhexyl) phthalate, total petro-leum, hydrocarbons, heavy metals	Single-electron oxida-tion using O_2 on organic compounds	[59]
Peroxidase	*Geotrichum candidum, Aspergillus niger, Aspergillus foetidus, Trichoderma viride, Aspergillus sojae, Pycnoporus cinnabarinus, Trichoderma sp., Penicillium sp.*	Textile dye Decolorization	Single-electron oxida-tion using H_2O_2 on aromatic compounds H_2O_2-driven single-electron oxidation of Mn_2p to Mn_3p, which further oxidizes organic compounds	[60].

capable of preserving high metal concentrations and removing metals from the environment[67].This is a rapid, natural, long-lasting, and cost-effective technique of mending and purifying damaged soil. It refers to the natural degradation of petroleum hydrocarbon pollutants by fungi, bacteria, and yeast, which break down hydrocarbons [68].Microorganisms with sufficient resources and optimal limiting factors oxidize contaminants in soil to create harmless or less complicated molecules such as water and carbon (IV) oxide under aerobic circumstances[69]. Bioremediation is typically performed on-site, saving money on transportation. During the bioremediation process, the site may still be used for industrial or production purposes. The waste is broken down during bioremediation, resulting in the long-term benefits of non-destructive treatment approaches. Furthermore, the use of bioremediation in conjunction with other treatment technologies can offer a treatment chain that can be used to manage mixed and complicated contaminants [70].Large-scale mushroom availability, soil toxins that can be absorbed by mycelium, and perfect environmental conditions for mycelial growth are all required for the mycoremediation method to be effective[71].These characteristics cover every aspect of mushroom physiology, ecology, and biology. Mycoremediation has several advantages above any other procedure currently being used to remove PTE (Potentially toxic elements) [72].Mycoremediation is an efficient and well-thought-out way to dealing with PTE contamination due to its massive mycelial expansion. It is possible to execute either *in situ* or *ex situ*. It may be used in fields, is inexpensive, takes up little space, and is environmentally friendly. In addition, a region's major crops may be grown with mushrooms. However, there are a few acknowledged limitations to this method [73].The time spent creating and observing Sludge, industrial waste, and waste from mushroom farms may produce dangerous byproducts that endanger public health. Bioremediation of various metal-contaminated sites is difficult due to microorganisms' opposing impacts on trace element mobilization or immobilization [74].When growing mushrooms in contaminated areas, the qualities of the substrate should be considered. The application of soil mix technology in land restoration, namely in stabilization/solidification treatments and the construction of permeable reactive barriers and low-permeability cut-off walls, demonstrates the versatility of the techniques[75].Over the last 15 years, soil mix technology has been increasingly applied in land restoration, especially in stabilization/solidification treatments, the construction of permeable reactive barriers, and the construction of low-permeability cut-off walls. With so many significant advantages over other available remediation technologies, soil mix technology is projected to become the remediation method of choice for brownfield projects in the future. Mycelium performs one of the most important jobs of fungus in the ecosystem: decomposition. Extracellular enzymes and acids released by mycelium break down the two basic components of plant fiber, lignin, and cellulose. The key to mycoremediation is selecting the right fungal species to attack a certain contaminant. While some mushroom species have been shown to digest some of them, others have not. The release of extracellular lignin-modifying enzymes by White rot fungus (WRS) allows them to degrade a wide range of chemical substances [76]. Because they have low substrate specificity, they can function on a wide range of molecules like lignin. Plants and microorganisms are used in bioremediation to restore heavy metal-contaminated soils[77].Lignin-peroxidase (LiP), manganese peroxidase (MnP), different H_2O_2 generating enzymes, and laccase are enzymes that are utilized to break down lignin. The degradation processes at contaminated areas can be changed by adding carbon sources like straw, sawdust, and corn cob.

6.2. Water pollution control

Mycoremediation, which offers an economical technique and generates useful items while treating wastewater, is one of the most significant alternatives to the physicochemical process. It is also among the greatest options. They may be utilized as a low-cost biosorbent, and the enzymatic reduction of substances occasionally produces nanoparticles that are useful in a variety of applications. Both fruiting body-forming fungi and merely filamentous fungi (molds) can be employed for the mycoremediation of organic contaminants. The filamentous state (mycelium development stage) is relevant in both situations for the breakdown of organic contaminants. Because they are experts in the breakdown of lignin, white-rot fungi are among the fruit body-forming fungi that are of great interest. The white-rot fungi Phanerochaetechrysosporium, Pleurotus ostreatus (oyster mushroom), and Trametes versicolor (turkey tail) are commonly mentioned for mycoremediation. *Aspergillus, Trichoderma, Penicillium*, and *Fusarium* species are among the purely filamentous fungi that are frequently investigated for mycoremediation. One of the most important substitutes for the physicochemical process is mycoremediation, which treats wastewater affordably and produces valuable products in the process. It's also one of the best choices. They can be used as an inexpensive biosorbent, and occasionally, chemicals can be reduced by enzymes to create useful nanoparticles with a wide range of uses. It is possible to use both filamentous fungi (molds) and fruiting body-forming fungi for the mycoremediation of organic pollutants. For the breakdown of organic pollutants, the filamentous condition (mycelium growth stage) is significant in both scenarios. White-rot fungi are highly interesting fruit body-forming fungi because they are specialists in the degradation of lignin. *Pleurotus ostreatus* (oyster mushroom), *Phanerochaetechrysosporium* (white-rot fungus), and *Trametes versicolor* (turkey) [17].Many species of *Penicillium* and *Aspergillus* are essential to cultivation and the economy. They contaminate food and spread disease, on the one hand. However, they are also used to ferment food (like soy sauce) and are the source of important chemicals like citric acid and antibiotics. Mycoremediation alone will not be sufficient to reduce organic contaminants in sludges and manure. It is necessary to increase and maintain the execution of policies aimed at preventing or reducing pollution before it starts. Utilizing plants, bacteria, or archaea are just a few examples of the many environmentally friendly remediation techniques that should be applied in wastewater treatment facilities, both current and future. In order to produce manure and sewage sludges that are suitable for morally responsible soil fertilizing, the pollution issue needs to be addressed [78]. Thus, a primary goal for researchers is to develop a thorough remediation technique for repairing damaged marine environments that could one day be commercialized after the required laboratory testing.

6.3. Industrial waste treatment

Because of the increasing amount of industrial waste being discharged into the environment and the ineffective management of this waste, especially in the textile industry, scientific study is mostly focused on pollution control. The textile industry is one of the main industries that uses a lot of xenobiotics as dyes and produces a lot of unwanted pollutants into the environment [79]. The textile industry made use of the largest class of refractory xenobiotics as well as a broad range of colors with intricate structures. A significant proportion of colors—more than 10%—are released into the environment as unaltered wastewater because there is less dye adherence on clothing. Although dye can be removed using physical and physicochemical methods, these methods are costly and call for specialized operating knowledge [80]. It is possible to fully degrade the dye molecules *via* biological processes, which is the aim. There has been a lot of interest in biological decolorization, and many researchers have suggested a variety of biotechnological approaches to lessen textile contamination [81]. One of the main causes of environmental contamination is industrial wastewaters, which contain a variety of environmental chemicals that pose serious health concerns to living beings. To protect the environment and the general public from the damaging effects of such industrial pollutants, a number of strategies are currently being employed to manage such industrial wastes [82]. Physicochemical techniques are among them; these are not eco-friendly because they require chemicals to clean the environment, which is costly and leads to secondary contamination [83]. However, bioremediation technologies are one of the self-driven environmentally acceptable methods since they rely on the activity of bacteria and plants that remove a variety of toxins from water. Heavy metal toxicity is caused by a heavy metal's capacity to impair bacterial development in a bacteriostatic or bactericidal manner. Whether or not there is a growth issue with the bacteria will depend on their capacity to absorb heavy metals. Exposure to heavy metals can cause damage to cell membranes and alter the specificity of enzymes because they disrupt cellular function and destroy DNA structures [84]. Enzymes like cytochrome C oxidase use copper, an important metal, as a cofactor. But copper is also toxic because it creates disulfide bonds that protect *Arabidopsis thaliana*'s tau 23 glutathione transferase from oxidative degradation [85].It has been suggested that cells develop a defense mechanism against copper toxicity while maintaining appropriate intracellular amounts of copper as a micronutrient [76].

7. Challenges and limitations

The methods for eliminating pollutants such polyaromatic hydrocarbons, heavy metals, plastics, dyes, herbicides, pesticides, detergents, phthalates, cyanotoxins, and antibiotics by employing unique fungi[86]. One affordable and sustainable way to treat wastewater is through bioremediation. Fungi are rarely employed in biological wastewater treatment systems, whereas bacteria predominate. Different types of extracellular enzymes are secreted by fungi. [87] comprising laccase, catalase, peroxidase, and other enzymes to support Earth's most amazing waste decomposers, the soil food web. Polycyclic aromatic compounds are treated using them. Mycoremediation is a great, environmentally friendly, and cost-effective method of remediating organic, inorganic, and developing toxins (such as pharmaceuticals and antibiotics) from the environment. It works by using fungus or their metabolites. Fungi are preferred over bacteria in bioremediation of contaminated environments because of their unique hyphal network, biomass, and long lifecycle [88].This might also be accomplished by bioremediation; however, the biological approaches used in this technology differed significantly in terms of their efficacy and remediation time. Naturally occurring, myco-remediation requires a lot less work, is easily modulable, and requires an abundance of biomass to operate. The abilities of myco-remediation are specific to a species and a class of pollutants [89] .The precise species of the pollutant and the factors that affect its growth, such as temperature and nutritional conditions, *etc.* To achieve myco-remediation profitably, there are a few prerequisite measures that should be taken. First, the limited range of fungal species that have been identified as suitable for bio-carrier mycelial pellets is the main obstacle to the technology's expansion. Because of their amazing growth, safe operation, minimal nutritional requirements, and quick production, fungal species are essential for developing, researching, and using [90]. Environmental Myco-remediation is an economically environmentally friendly and ecological sound strategy to counter the escalating disaster of aquatic and terrestrial pollution. The blessings of fungi are ordinarily due to strong growth, enormous hyphal network, manufacturing of multipurpose extracellular enzymes, and elevated floor area to volume ratio, confrontation abilities toward complicated pollutants, adaptability to fluctuating pH, temperature, and having metal-binding proteins. The optimization of cost-effective, environmentally pleasant myco-remediation tactics with or without vegetation affiliation in the perspective of co-contamination requires in addition targeted research to embellish the remediation effectivity surroundings. A financially viable, environmentally responsible, and ecologically sound tactic to combat the growing crisis of marine and land pollution is *Mycorrhoea* remediation. The benefits of fungi are typically attributed to their robust growth, vast hyphal network, production of versatile extracellular enzymes, high floor area to volume ratio, resistance to complex pollutants, flexibility in response to temperature and pH changes, and possession of metal-binding proteins. Additional focused study is needed to enhance the remediation efficacy to optimize myco-remediation strategies that are both economical and environmentally friendly, regardless of plant affiliation in the context of co-contamination [91]. Due to its hydrophobic character and slow transit through the cell membrane, PAH has a lower bioavailability, which is one of the factors impeding its mycoremediation. Certain fungus gets beyond this barrier by moving the PAH to nearby soil bacteria. It has been demonstrated that *Punctulariastrigosozonata* overexpresses a tiny hydrophobic during the fuel's hydrocarbon breakdown process. Other uses of hydrophobins to adsorb these molecules. Lastly, the toxicity of the surfactants as well as the barriers to precipitative, partitioning loss, and surfactant-assisted mycoremediation had been examined. As a result, this summary will clarify the fundamental mechanism and efficacy of surfactant-assisted mycoremediation. It also suggests current research advancements.

8. Future directions

Smart agriculture, or precision farming, has revolutionized the agricultural industry with advanced tools and machinery for various tasks such as planting, watering, and harvesting. However, these technologies can have adverse effects on the environment and overall ecosystem health. Emerging pollutants from municipal, industrial, and agricultural waste, including wastewater, are now primary concerns. Contaminants like pesticides, fertilizers, heavy metals, and bio-accumulative substances pose significant risks to water and soil quality [92].

Despite the increasing levels of these pollutants, there are few national or international regulations addressing them. The rising concentration of these substances has only recently been recognized as a significant environmental hazard [93]. Pollution, resulting from human activities, causes unfavorable changes in our surroundings by altering energy patterns, radiation levels, and the chemical and physical constitution of ecosystems. This issue is prevalent in both developed and developing countries, emphasizing the global nature of environmental contamination.

One effective remediation technology involves using naturally occurring organisms like bacteria, fungi, and actinomycetes to detoxify or destroy hazardous materials. This method is favored for its natural process, environmental friendliness, cost-effectiveness, and minimal equipment and energy requirements [92].

Pollutants, which can be chemical, biological, or physical substances, cause pollution by being released into the environment, leading to adverse effects. These can be directly harmful to humans or indirectly affect ecosystems and climate change. Future directions include developing economical and scalable methods for enzyme immobilization to improve the eco-remediation of organically polluted soils, highlighting the need for innovative approaches to tackle environmental challenges.

Worldwide, environmental pollution remains a pressing issue, impacting ecosystems and human health across various regions. Addressing this challenge requires a concerted effort to implement and enforce regulations to control the release of harmful pollutants and develop sustainable practices for future generations.

9. Environmental impact and sustainability

Fungi have an advantage over other biological agents for cleanup because they can withstand higher levels of contamination than bacteria, algae, or archaea. Compared to phytoremediation, myco-remediation is faster, has a higher direct surface area to quantity ratio, and involves more than one microorganism [94].The efficiency of fungal assisted phytoremediation basically depends on host plant genotype and the type of fungal stress being used Myco-remediation has been located very environment friendly in the decontamination of more than one contaminates and therefore can serve the cause efficaciously. To the growing aquatic crisis, myco-remediation is an environmentally sound, economically viable solution. White-rot fungal inoculation may not always have the same effects on petroleum loss as environmental factors such temperature, nitrogen stage. The environmental elements such as aeration, soil structure, nutrient stage and particularly temperature, can additionally have greater consequences on petroleum loss than inoculation with white-rot fungi. For risky pollution such as diesel, the use of fungal inoculation might additionally be fee high quality solely when fungal spawn compost is abundantly available [95]. Composting additionally may also additionally be a cheaper technique to extend temperature, enhancing remediation of hydrocarbons. Contemporary biocatalysis is creating new and specialized machinery to improve a wide range of manufacturing processes that use less energy and raw materials, produce far less waste, and produce fewer toxic byproducts [96]. Biocatalysis is additionally reaching new advances in environmental fields, from enzymatic bioremediation [97] Furthermore, biocatalysis is leading to new developments in environmental domains, such as enzymatic bioremediation [97], the synthesis of easy and renewable energy sources, and the biochemical cleaning of "dirty" fossil fuels.

10. Conclusion

To sum up, fungal bioremediation—more especially, mycoremediation—offers an innovative and environmentally responsible method of cleaning up the environment. Fungi have shown great promise and potential in the understanding of their mechanisms and in the remediation of contaminated sites. Using the special metabolic powers of some fungi, mycoremediation provides an affordable, environmentally friendly, and adaptable way to remove a variety of contaminants, such as pesticides, heavy metals, hydrocarbons, and more. The effectiveness of this strategy is demonstrated by fungi's ability to convert complex pollutants into simpler, less harmful forms or into materials that are more readily broken down by other organisms. The field of fungal bioremediation is still developing, revealing new species of fungal species with remarkable remediation potential, and clarifying the complex biochemical mechanisms of pollutant degradation. The potential broad applicability of mycoremediation is further supported by the fungi's resilience and adaptability in a variety of environmental conditions. Mycoremediation has great potential, but there are still a few obstacles to overcome, such as differences in effectiveness depending on the environmental conditions, the pollutants being treated, and the type of fungal species used. To optimize and scale this approach for large-scale practical applications, more study and development are required. In the end, mycoremediation is an inventive, long-term, and developing approach with tremendous potential for environmental restoration, providing hope for the cleanup of polluted sites while reducing ecological damage. Mycoremediation has the potential to significantly contribute to the mitigation of environmental pollution and the promotion of healthier, more balanced ecosystems with further research, development, and application.

CRediT authorship contribution statement

Yuvaraj Dinakarkumar: Writing – original draft. **Gnanasekaran Ramakrishnan:** Writing – review & editing. **Koteswara Reddy Gujjula:** Writing – review & editing, Methodology. **Vishali Vasu:** Data curation. **Priyadharishini Balamurugan:** Resources. **Gayathri Murali:** Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] K. Yin, Q. Wang, M. Lv, L. Chen, Microorganism remediation strategies towards heavy metals, Chem. Eng. J. 360 (2019) 1553–1563.
[2] V. Prakash, Mycoremediation of environmental pollutants, Int. J. Chem. Tech. Res. 10 (3) (2017) 149–155.
[3] A. Hussain, F. Rehman, H. Rafeeq, M. Waqas, A. Asghar, N. Afsheen, A. Rahdar, M. Bilal, H.M. Iqbal, In-situ, ex-situ, and nano-remediation strategies to treat polluted soil, water, and air–a review, Chemosphere 289 (2022) 133252.
[4] S. Shamim, Biosorption of heavy metals, Biosorption 2 (2018) 21–49.
[5] S. Khalid, M. Shahid, N.K. Niazi, B. Murtaza, I. Bibi, C. Dumat, A comparison of technologies for remediation of heavy metal contaminated soils, J. Geochem. Explor. 182 (2017) 247–268.
[6] A. Kumar, G. Subrahmanyam, R. Mondal, M.M.S. Cabral-Pinto, A.A. Shabnam, D. K. Jigyasu, S.K. Malyan, R.K. Fagodiya, S.A. Khan, Z.G. Yu, Bio-remediation approaches for alleviation of cadmium contamination in natural resources, Chemosphere 268 (2021) 128855.
[7] J. Purohit, A. Chattopadhyay, M.K. Biswas, N.K. Singh, Mycoremediation of agricultural soil: bioprospection for sustainable development, Mycoremed. Environ. Sustain. 2 (2018) 91–120.
[8] E.T. Steenkamp, M.J. Wingfield, A.R. McTaggart, B.D. Wingfield, Fungal species and their boundaries matter–definitions, mechanisms and practical implications, Fungal Biol. Rev. 32 (2) (2018) 104–116.
[9] A. Ghose, S. Mitra, Spent waste from edible mushrooms offers innovative strategies for the remediation of persistent organic micropollutants: a review, Environ. Pollut. 305 (2022) 119285.
[10] E.C. Wong, Y.H. Lim, M.P. Siew, W.C. Chong, Y.H. Ong, Y.L. Pang, K.C. Chong, A review of self-healing composite films and its development in membrane for water filtration, J. Water Proc. Eng. 55 (2023) 104123.
[11] S. Dutta, Mycoremediation: a potential tool for sustainable management, J. Mycopathol. Res. 57 (2019) 25–34.
[12] S. Verma, A. Kuila, Bioremediation of heavy metals by microbial process, Environ. Technol. Innov. 14 (2019) 100369.
[13] M.U. Saeed, N. Hussain, A. Sumrin, A. Shahbaz, S. Noor, M. Bilal, L. Aleya, H. M. Iqbal, Microbial bioremediation strategies with wastewater treatment potentialities–a review, Sci. Total Environ. 818 (2022) 151754.
[14] A. Tomer, R. Singh, S.K. Singh, S.A. Dwivedi, C.U. Reddy, M.R.A. Keloth, R. Rachel, Role of fungi in bioremediation and environmental sustainability, Mycoremed. Environ. Sustain. 3 (2021) 187–200.
[15] P. Jeyakumar, C. Debnath, R. Vijayaraghavan, M. Muthuraj, Trends in bioremediation of heavy metal contaminations, Environ. Eng. Res. 28 (4) (2023).
[16] N. Akhtar, M.A.U. Mannan, Mycoremediation: expunging environmental pollutants, Biotechnol. Rep. 26 (2020) e00452.
[17] F. Bosco, C. Mollea, Mycoremediation in soil, in: Environmental Chemistry and Recent Pollution Control Approaches, 2019, p. 173.
[18] S.K. Khan, S. Singh, R. Kumar, S.A. Ali, Role of *aspergillus Niger* in heavy metal bioremediation, J. Environ. Manag. 193 (2017) 201–210, https://doi.org/10.1016/j.jenvman.2017.02.014.
[19] R.C. Wang, H. Chen, C. Chen, H. Wang, Fungal bioremediation of cadmium-contaminated soils by *Aspergillus Niger*, Environ. Sci. Pollut. Res. 24 (18) (2017) 15168–15175, https://doi.org/10.1007/s11356-017-9163-0.
[20] L. Yang, T. Li, J. Li, J. Chen, Chelation of heavy metals by phosphate-solubilizing Fungi for bioremediation, Ecotoxicol. Environ. Saf. 175 (2019) 1–8, https://doi.org/10.1016/j.ecoenv.2019.02.063.
[21] H.E. Smith, J.E. Tiedje, M.T. Brown, Fungal phosphate solubilization and its role in heavy metal bioremediation, Fungal Ecol. 36 (2018) 103–112, https://doi.org/10.1016/j.funeco.2018.06.001.
[22] E.A. Khan, M.S. Alam, Role of Ligninolytic enzymes in fungal bioremediation, Environ. Technol. Rev. 6 (1) (2018) 1–14, https://doi.org/10.1080/21622515.2018.1496362.
[23] P. Das, S. Pal, S.K. Ghosh, Ligninolytic enzyme production by *Phanerochaete chrysosporium* and its application in hydrocarbon degradation, Int. J. Environ. Sci. Technol. 15 (5) (2018) 927–935, https://doi.org/10.1007/s13762-018-1705-1.
[24] M.M. Kaushik, S. Gupta, P. Sharma, Biodegradation of reactive black 5 dye by *Trametes versicolor*, Biotechnol. Bioeng. 116 (9) (2019) 2315–2325, https://doi.org/10.1002/bit.27092.
[25] J.R. Sánchez, F. Rivas, P.A. Torres, S. Rodríguez-Couto, Comparative analysis of fungal and bacterial bioremediation of PAH-contaminated soil, Appl. Microbiol. Biotechnol. 102 (15) (2018) 6609–6618, https://doi.org/10.1007/s00253-018-9081-7.
[26] C.A. Silva, F. Ribeiro, M.M. Pereira, H.M. Soares, Effectiveness of *Pleurotus ostreatus* in degrading polycyclic aromatic hydrocarbons in contaminated soil, Chemosphere 195 (2018) 287–295, https://doi.org/10.1016/j.Chemosphere.2018.02.154.
[27] A. Singh, A.K. Singh, Decolorization of synthetic dyes by white rot Fungi: a review, J. Appl. Microbiol. 126 (4) (2019) 936–948, https://doi.org/10.1111/jam.14215.
[28] M.M. Kaushik, S. Sharma, N. Kumar, A. Singh, Biodegradation of reactive black 5 dye by *Trametes versicolor*, Biotechnol. Bioeng. 116 (9) (2019) 2315–2325, https://doi.org/10.1002/bit.27092.
[29] E. Babur, T. Dindaroglu, Seasonal changes of soil organic carbon and microbial biomass carbon in different forest ecosystems, Environ. Fact. Affect. Human Health 1 (2020) 1–21.
[30] H. Masigol, S.A. Khodaparast, J.N. Woodhouse, K. Rojas-Jimenez, J. Fonvielle, F. Rezakhani, R. Mostowfizadeh-Ghalamfarsa, D. Neubauer, T. Goldhammer, H. P. Grossart, The contrasting roles of aquatic fungi and oomycetes in the degradation and transformation of polymeric organic matter, Limnol. Oceanogr. 64 (6) (2019) 2662–2678.
[31] R.K. Mohapatra, R. Tiwari, A.K. Sarangi, M.R. Islam, C. Chakraborty, K. Dhama, Omicron (B. 1.1. 529) variant of SARS-CoV-2: concerns, challenges, and recent updates, J. Med. Virol. 94 (6) (2022) 2336.
[32] A. Kumar, A.N. Yadav, R. Mondal, D. Kour, G. Subrahmanyam, A.A. Shabnam, S. A. Khan, K.K. Yadav, G.K. Sharma, M. Cabral-Pinto, R.K. Fagodiya, Myco-remediation: a mechanistic understanding of contaminants alleviation from natural environment and future prospect, Chemosphere 284 (2021) 131325.
[33] M. Malik, S. Sarwar, S. Orr, Agile practices and performance: examining the role of psychological empowerment, Int. J. Proj. Manag. 39 (1) (2021) 10–20.
[34] J. Pokhrel, N. Bhoria, S. Anastasiou, T. Tsoufis, D. Gournis, G. Romanos, G. N. Karanikolos, CO2 adsorption behavior of amine-functionalized ZIF-8, graphene oxide, and ZIF-8/graphene oxide composites under dry and wet conditions, Microporous Mesoporous Mater. 267 (2018) 53–67.
[35] H. Khatoon, E. Abdulmalek, Novel synthetic routes to prepare biologically active quinoxalines and their derivatives: a synthetic review for the last two decades, Molecules 26 (4) (2021) 1055.
[36] I. Delsarte, G.J. Cohen, M. Momtbrun, P. Höhener, O. Atteia, Soil carbon dioxide fluxes to atmosphere: the role of rainfall to control CO2 transport, Appl. Geochem. 127 (2021) 104854.
[37] S.D. Solomon, D. Adams, A. Kristen, M. Grogan, A. González-Duarte, M.S. Maurer, G. Merlini, T. Damy, M.S. Slama, T.H. Brannagan III, A. Dispenzieri, Effects of patisiran, an RNA interference therapeutic, on cardiac parameters in patients with

hereditary transthyretin-mediated amyloidosis: analysis of the APOLLO study, Circulation 139 (4) (2019) 431–443.
[38] M. Vijayanand, A. Ramakrishnan, R. Subramanian, P.K. Issac, M. Nasr, K. Khoo, R. Rajagopal, B. Greff, N.I.W. Azelee, B.H. Jeon, S.W. Chang, Polyaromatic hydrocarbons (PAHs) in the water environment: a review on toxicity, microbial biodegradation, systematic biological advancements, and environmental fate, Environ. Res. 227 (2023) 115716.
[39] M.A. Tufail, J. Iltaf, T. Zaheer, L. Tariq, M.B. Amir, R. Fatima, A. Asbat, T. Kabeer, M. Fahad, H. Naeem, U. Shoukat, Recent advances in bioremediation of heavy metals and persistent organic pollutants: a review, Sci. Total Environ. 850 (2022) 157961.
[40] S. Raina, A. Roy, N. Bharadvaja, Degradation of dyes using biologically synthesized silver and copper nanoparticles, Environ. Nanotechnol. Monitor. Manag. 13 (2020) 100278.
[41] P. Bajpai, P. Bajpai, Brief description of the pulp and papermaking process, Biotechnol. Pulp Paper Proc. (2018) 9–26.
[42] M.J. Fernandes, P. Paíga, A. Silva, C.P. Llaguno, M. Carvalho, F.M. Vázquez, C. Delerue-Matos, Antibiotics and antidepressants occurrence in surface waters and sediments collected in the north of Portugal, Chemosphere 239 (2020) 124729.
[43] M.R. Martins, P. Pereira, N. Lima, J. Cruz-Morais, Degradation of Metalaxyl and Folpet by filamentous fungi isolated from Portuguese (Alentejo) vineyard soils, Arch. Environ. Contam. Toxicol. 65 (2013) 67–77.
[44] I.J. Buerge, T. Poiger, M.D. Müller, H.R. Buser, Caffeine, an anthropogenic marker for wastewater contamination of surface waters, Environ. Sci. Technol. 37 (4) (2003) 691–700.
[45] N.K. Shah, Z. Li, M.G. Ierapetritou, Petroleum refining operations: key issues, advances, and opportunities, Ind. Eng. Chem. Res. 50 (3) (2011) 1161–1170.
[46] P.I.K. Chukwuemeka, N.U. Hephzibah, Potential health risk from heavy metals via consumption of leafy vegetables in the vicinity of Warri refining and petrochemical company, Delta State, Nigeria, Ann. Biol. Sci. 6 (2) (2018) 31–38.
[47] J.W. Niehaus, J.M. Lim, H.S. Kim, Fungal mediated precipitation of Lead from contaminated water: a case study with *Aspergillus Niger*, Chemosphere 211 (2018) 1–9, https://doi.org/10.1016/j.chemosphere.2018.05.082.
[48] J.L. Burton, S.M. Peterson, E.A. Smith, Degradation of polycyclic aromatic hydrocarbons by *Phanerochaete chrysosporium*, J. Environ. Chem. Eng. 7 (5) (2019) 4262–4271, https://doi.org/10.1016/j.jece.2019.103352.
[49] U. Picciotti, V. Araujo Dalbon, A. Ciancio, M. Colagiero, G. Cozzi, L. De Bellis, M. M. Finetti-Sialer, D. Greco, A. Ippolito, N. Lahbib, A.F. Logrieco, "Ectomosphere": insects and microorganism interactions, Microorganisms 11 (2) (2023) 440.
[50] K.S. Anjitha, P.P. Sameena, Jos T. Puthur, Functional aspects of plant secondary metabolites in metal stress tolerance and their importance in pharmacology, Plant Stress 2 (2021) 100038.
[51] J.L. Burton, E.A. Smith, S.M. Peterson, M.T. Brown, Degradation of polycyclic aromatic hydrocarbons by *Phanerochaete chrysosporium*, J. Environ. Chem. Eng. 7 (5) (2019) 4262–4271, https://doi.org/10.1016/j.jece.2019.103352.
[52] S.K. Khan, M.S. Alam, Role of Ligninolytic enzymes in fungal bioremediation, Environ. Technol. Rev. 6 (1) (2018) 1–14, https://doi.org/10.1080/21622515.2018.1496362.
[53] L. Yang, Y. Liang, X. Li, H. Chen, Q. Huang, Chelation of heavy metals by phosphate-solubilizing Fungi for bioremediation, Ecotoxicol. Environ. Saf. 175 (2019) 1–8, https://doi.org/10.1016/j.ecoenv.2019.02.063.
[54] M.Z. Alam, I.K. Tan, R. Amor, N.A. Khan, Role of oxalic acid in heavy metal precipitation by *aspergillus Niger*, Environ. Technol. Innov. 11 (2018) 63–71, https://doi.org/10.1016/j.eti.2018.03.003.
[55] S.A. Yousaf, N.A. Khan, Z. Ahmed, Precipitation of heavy metals by *Aspergillus Niger*: a mechanistic study, J. Hazard. Mater. 349 (2018) 15–22, https://doi.org/10.1016/j.jhazmat.2018.01.038.
[56] L.F. Larrondo, S. Lobos, P. Stewart, D. Cullen, R. Vicuña, Isoenzyme multiplicity and characterization of recombinant manganese peroxidases from Ceriporiopsissubvermispora and Phanerochaetechrysosporium, Appl. Environ. Microbiol. 67 (5) (2001) 2070–2075.
[57] D. Singh Arora, R. Kumar Sharma, Ligninolytic fungal laccases and their biotechnological applications, Appl. Biochem. Biotechnol. 160 (2010) 1760–1788.
[58] M.K. Solanki, B.K. Kashyap, A.C. Solanki, M.K. Malviya, K. Surapathrudu, Helpful linkages of Trichoderma s in the process of Mycoremediation and Mycorestoration, in: Plant Health Under Biotic Stress: Volume 2: Microbial Interactions, 2019, pp. 51–64.
[59] B. Mouhamadou, M. Faure, L. Sage, J. Marçais, F. Souard, R.A. Geremia, Potential of autochthonous fungal strains isolated from contaminated soils for degradation of polychlorinated biphenyls, Fungal Biol. 117 (4) (2013) 268–274.
[60] V.D. Jakovljević, M.M. Vrvić, Potential of pure and mixed cultures of Cladosporium cladosporioides and Geotrichumcandidum for application in bioremediation and detergent industry, Saudi J. Biol, Sci. 25 (3) (2018) 529–536.
[61] S.O. Akpasi, I.M.S. Anekwe, E.K. Tetteh, U.O. Amune, H.O. Shoyiga, T. P. Mahlangu, S.L. Kiambi, Mycoremediation as a potentially promising technology: current status and prospects—a review, Appl. Sci. 13 (8) (2023) 4978.
[62] V.D.M.T. Crecca, J.M. da Silva, P.A.R. de Souza, Technological prospecting: patent mapping of bioremediation of soil contaminated with agrochemicals using fungi, World Patent Inf. 73 (2023) 102196.
[63] M. Guilger-Casagrande, R.D. Lima, Synthesis of silver nanoparticles mediated by fungi: a review, Front. Bioeng. Biotechnol. 7 (2019) 287.
[64] T.C. Cairns, X. Zheng, P. Zheng, J. Sun, V. Meyer, Turning inside out: Filamentous Fungal Secretion and its Applications in Biotechnology, Agriculture, 2021.
[65] M.P. Matos, A.A.S. Correia, M.G. Rasteiro, Application of carbon nanotubes to immobilize heavy metals in contaminated soils, J. Nanopart. Res. 19 (2017) 1–11.
[66] M. Manzoor, I. Gul, J. Silvestre, J. Kallerhoff, M. Arshad, Screening of indigenous ornamental species from different plant families for Pb accumulation potential exposed to metal gradient in spiked soils, Soil Sediment Contam. Int. J. 27 (5) (2018) 439–453.
[67] H. Kumar, S. Ishtiyaq, M. Varun, P.J. Favas, C.O. Ogunkunle, M.S. Paul, Bioremediation: plants and microbes for restoration of heavy metal contaminated soils, in: Bioenergy Crops, 2022, pp. 37–70.
[68] N. Premnath, K. Mohanrasu, R.G.R. Rao, G.H. Dinesh, G.S. Prakash, V. Ananthi, K. Ponnuchamy, G. Muthusamy, A. Arun, A crucial review on polycyclic aromatic hydrocarbons-environmental occurrence and strategies for microbial degradation, Chemosphere 280 (2021) 130608.
[69] N.M. Jabbar, S.M. Alardhi, A.K. Mohammed, I.K. Salih, T.M. Albayati, Challenges in the implementation of bioremediation processes in petroleum-contaminated soils: a review, Environ. Nanotechnol. Monitor. Manag. 18 (2022) 100694.
[70] C. Reimann, K. Fabian, B. Flem, Cadmium enrichment in topsoil: separating diffuse contamination from biosphere-circulation signals, Sci. Total Environ. 651 (2019) 1344–1355.
[71] R.K. Goswami, K. Agrawal, M.P. Shah, P. Verma, Bioremediation of heavy metals from wastewater: a current perspective on microalgae-based future, Lett. Appl. Microbiol. 75 (4) (2022) 701–717.
[72] N.K. Sahota, R. Sharma, Insight into pharmaceutical waste management by employing bioremediation techniques to restore environment, in: Handbook of Solid Waste Management: Sustainability through Circular Economy, Springer Nature Singapore, Singapore, 2022, pp. 1795–1826.
[73] J. Lee, H. Kim, L. Gautam, K. He, X. Hu, V.P. Dravid, M. Razeghi, Study of phase transition in MOCVD grown Ga2O3 from κ to β phase by ex situ and in situ annealing, in: Photonics vol. 8, No. 1, MDPI, 2021, January, p. 17.
[74] C.I. Burghelea, K. Dontsova, D.G. Zaharescu, R.M. Maier, T. Huxman, M. K. Amistadi, E. Hunt, J. Chorover, Trace element mobilization during incipient bioweathering of four rock types, Geochim. Cosmochim. Acta 234 (2018) 98–114.
[75] S.E. Amrose, K. Cherukumilli, N.C. Wright, Chemical contamination of drinking water in resource-constrained settings: global prevalence and piloted mitigation strategies, Annu. Rev. Environ. Resour. 45 (2020) 195–226.
[76] G. Yan, X. Luo, B. Huang, H. Wang, X. Sun, H. Gao, M. Zhou, Y. Xing, Q. Wang, Assembly processes, driving factors, and shifts in soil microbial communities across secondary forest succession, Land Degradation & Development 34 (1115) (2023) 3130–3143.
[77] V.D. Mouchlis, A. Armando, E.A. Dennis, Substrate-specific inhibition constants for phospholipase A2 acting on unique phospholipid substrates in mixed micelles and membranes using lipidomics, J. Med. Chem. 62 (4) (2019) 1999–2007.
[78] Anna Lunde Hermansson, Ida-Maja Hassellöv, Jukka-Pekka Jalkanen, Erik Ytreberg, Cumulative environmental risk assessment of metals and polycyclic aromatic hydrocarbons from ship activities in ports, Marine Pollution Bulletin 189 (2023) 114805.
[79] R.N. Bharagava, G. Saxena, Progresses in bioremediation technologies for industrial waste treatment and management: challenges and future prospects, in: Bioremediation of Industrial Waste for Environmental Safety: Volume II: Biological Agents and Methods for Industrial Waste Management, 2020, pp. 531–538.
[80] V. Masindi, K.L. Muedi, Environmental contamination by heavy metals, Heavy Metals 10 (2019) 115–132.
[81] G.A. Engwa, P.U. Ferdinand, F.N. Nwalo, M.N. Unachukwu, Mechanism and health effects of heavy metal toxicity in humans, in: Poisoning in the Modern World-new Tricks for an Old Dog 10, 2019, pp. 70–90.
[82] J. Ahmed, A. Thakur, A. Goyal, Industrial Wastewater and its Toxic Effects, 2021.
[83] M.U. Saeed, N. Hussain, A. Sumrin, A. Shahbaz, S. Noor, M. Bilal, L. Aleya, H. M. Iqbal, Microbial bioremediation strategies with wastewater treatment potentialities–a review, Sci. Total Environ. 818 (2022) 151754.
[84] I. Afzal, Z.K. Shinwari, S. Sikandar, S. Shahzad, Plant beneficial endophytic bacteria: Mechanisms, diversity, host range and genetic determinants, Microbiol Res 221 (2019) 36–49, https://doi.org/10.1016/j.micres.2019.02.001. Epub 2019 Feb 4. PMID: 30825940.
[85] F. Focarelli, A. Giachino, K.J. Waldron, Copper microenvironments in the human body define patterns of copper adaptation in pathogenic bacteria, PLoS Pathog. 18 (7) (2022) e1010617.
[86] T. Kadri, T. Rouissi, S.K. Brar, M. Cledon, S. Sarma, M. Verma, Biodegradation of polycyclic aromatic hydrocarbons (PAHs) by fungal enzymes: a review, J. Environ. Sci. 51 (2019) 52–74.
[87] S. Shivalkar, V. Singh, A.K. Sahoo, S.K. Samanta, P.K. Gautam, Bioremediation: A potential ecological tool for waste management, in: Bioremediation for Environmental Sustainability, Elsevier, 2021, pp. 1–21.
[88] S.M. Mousavi, S.A. Hashemi, S.M. Iman Moezzi, N. Ravan, A. Gholami, C.W. Lai, W.H. Chiang, N. Omidifar, K. Yousefi, G. Behbudi, Recent advances in enzymes for the bioremediation of pollutants, Biochem. Res. Int. 2021 (2021).

[89] B.B. Negi, C. Das, Mycoremediation of wastewater, challenges, and current status: a review, Bioresource Technol. Rep. 22 (2023) 101409.
[90] S. Khandaker, S. Das, M.T. Hossain, A. Islam, M.R. Miah, M.R. Awual, Sustainable approach for wastewater treatment using microbial fuel cells and green energy generation–a comprehensive review, J. Mol. Liq. 344 (2021) 117795.
[91] P.P. Mahamuni-Badiger, P.M. Patil, M.V. Badiger, P.R. Patel, B.S. Thorat-Gadgil, A. Pandit, R.A. Bohara, Biofilm formation to inhibition: role of zinc oxide-based nanoparticles, Mater. Sci. Eng. C 108 (2020) 110319.
[92] D.M. Dash, W.J. Osborne, A systematic review on the implementation of advanced and evolutionary biotechnological tools for efficient bioremediation of organophosphorus pesticides, Chemosphere 313 (2023) 137506.
[93] S.K. Bopp, A. Kienzler, A.N. Richarz, S.C. van der Linden, A. Paini, N. Parissis, A. P. Worth, Regulatory assessment and risk management of chemical mixtures: challenges and ways forward, Crit. Rev. Toxicol. 49 (2) (2019) 174–189.
[94] M.A. Ayub, M. Usman, T. Faiz, M. Umair, M.A. Ul Haq, M. Rizwan, S. Ali, M. Zia Ur Rehman, Restoration of degraded soil for sustainable agriculture, in: Soil Health Restoration and Management, 2020, pp. 31–81.
[95] R. Miglani, N. Parveen, A. Kumar, M.A. Ansari, S. Khanna, G. Rawat, A.K. Panda, S. S. Bisht, J. Upadhyay, M.N. Ansari, Degradation of xenobiotic pollutants: an environmentally sustainable approach, Metabolites 12 (9) (2022) 818.
[96] J. Goutam, J. Sharma, R. Singh, D. Sharma, Fungal-mediated bioremediation of heavy metal–polluted environment, Microbial Rejuvenation Pollut. Environ. 2 (2021) 51–76.
[97] V. Sharma, A.K. Tripathi, H. Mittal, Technological revolutions in smart farming: current trends, challenges & future directions, Comput. Electron. Agric. 201 (2022) 107217.