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Review Article

An Overview on Role of Fungi In the Bioremediation of Some Pollutants

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A B S T R A C T

Increasing environmental pollution is one of today's problems, posing a major threat to ecological balance. Increasing human activities such as urbanization, industrialization, technological development, and agricultural methods have significantly contributed to this imbalance. Hence, the development of suitable sustainable treatment methods is one of the global concerns for the eradication of pollutants from polluted environments. One of the proposed methods for this purpose is the use of fungi. So, this review will discuss the role of fungi in the bioremediation of some pollutants. Keywords such as "bioremediation", fungi", "plastic degradation", "mineral degradation", "pesticides", "pharmaceutical active compounds", "heavy metal", and "wastewater" were searched. Articles published in databases, such as Google Scholar, PubMed/ MEDLINE, and other scientific databases, were used. The results of this study showed that fungi can play a role in the bioremediation of plastic, mineral, pesticides, pharmaceutical active compounds, heavy metals, and wastewater.

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Introduction

Bioremediation is an effective cleaning process in which harmful pollutants are removed from the environment using various microorganisms or their enzymes. Environmental pollution is one of the most important problems in the world due to the uncontrolled discharge of sewage and untreated pollutants into the environment, and population growth, industrialization, exploration, urbanization and mining are the main actors of environmental pollution. In addition, multiple pollutants, which refer to the simultaneous occurrence of more than one type of pollutant in any ecosystem, are one of the most serious concerns [1]. Water quality has deteriorated as a result of human activities, such as mining and the final disposal of toxic metal effluents from steel mills, battery companies, and electricity generation, which pose major environmental concerns. Wastes such as oil, polyethylene and rare metals harm the environment. Heavy metals can exist in nature in the earth's crust and are difficult to decompose [2]. The repeated interaction of some persistent organic pollutants leads to the possibility of infection persistence, especially in unique habitats such as northern latitudes, seabed areas, dunes, and marshes that have insufficient ability to cope with these pollutants. Different types of plants and microorganisms are able to remove some of these dangerous pollutants [3]. Microorganisms are important in decomposition, detoxification, and even accumulation of harmful organic and inorganic compounds [4]. There are reports on the cleanup/detoxification of various types of pollutants, including the use of microorganisms such as bacteria and fungi in environmental samples, such as soil and water. Fungi are among the microorganisms whose role in bioremediation has been mentioned [5]. This review provides an overview of pollutants and the role of fungi in bioremediation and important geological processes.

An overview of fungi

The fungal kingdom is incredibly diverse, comprising more than two hundred orders and dozens of phyla, with new ones being described constantly [6-8]. These 12 phyla are divided into six main groups: the suborders Dikarya (including the phyla Ascomycota, Basidiomycota, and Entorrhizomycota) and Chytridiomyceta (including the phyla Chytridiomycota, Monoblepharidomycota, and Neocallimastigomycota), the phyla Mucoromycota, Zoopagomycota, and Blastocladiomycota, and the main group Opisthosporidia (including the phyla Aphelidiomycota, Cryptomycota/ Rozellomycota, and Microsporidia, and is possibly paraphyletic) [6, 7]. Fungi exhibit a wide range of feeding lifestyles, morphologies, growth patterns, and ecologies that play a vital role in terrestrial and aquatic ecosystems [7,9,10]. Some fungi exist as natural flora in the human body and some exist in the surrounding environment in air, water, soil, sewage, plants, wood, etc [11-20]. It is estimated that approximately 25% of Earth's biomass is made up of fungi [17]. Som fungi

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can play a role in bioremediation [21], wich we will discuss further.

The role of fungi in plastic degradation

Plastic pollution has become a distinctive element of the global world, and the expansion and use of plastic in the consumer and commercial sectors has given this material a permanent place in human life, which has contributed to increasing environmental pollution with negative effects on our ecosystems and some ecological functions of natural habitats. Fungi degrade plastic polymers through attachment, cloning and further degradation. It has been shown that the morphology of the polymer surface can be strongly affected by fungal activity and may be associated with crack formation [21]. Fungi seem to degrade polymer by using it as their sole carbon source [22]. In fungal binding, laccases play an important role as polycopper oxidases that oxidize a wide variety of substrates including polymers, lignin, and polyvinyl chloride [23]. It is reported that two laccase genes named AFLA_006190 and AFLA_053930 showed high expression during degradation process of high-density polyethylene [24]. It has been shown that various enzymes including: cutinases, xylanases, pectinases, amylases, glucanases, and lipases are used during the degradation process [21, 25]. It has recently been shown that enzymes are not used alone, but synergistically to enhance efficiency [25]. Among the fungi, basidiomycetes and ascomycetes have shown good performance in the biodegradation of plastic in laboratory conditions [21]. Some fungal species with the ability to degrade polymers are listed in the Table 1.

The role of fungi in mineral degradation

Silicate minerals are the most common minerals that make up 90% of minerals, including: phosphates, sulfides, and carbonate oxides, as well as the vast majority of mineral metals. They can also be dissolved by weathering processes. Some of these metals are essential for life, while others, such as industrial agents and agricultural fields, are toxic to organisms and humans, leading to pollution of the hydrosphere, lithosphere, and Earth [26]. Remediation processes, via physical and chemical techniques, can be expensive and economically inappropriate, and their performance may be difficult to assess, so scientists focus on using organisms to remove pollutants from the environment through different mechanisms depending on the type of organism and the pollutants [26, 27]. The interaction between microbes and minerals plays a significant role in bioremediation, which is the most effective strategy for removing pollutants from soil, water, and even the atmosphere. For this purpose, the use of organisms, especially various fungal and bacterial species, has been investigated due to their ability to survive in different environments contaminated with toxic metals, radioactive materials, and other industrial waste materials [26]. Fungi play an important role in bioremediation processes due to their surveillance and diverse mechanisms in interacting with various surfaces under different conditions [26, 28, 29]. Fungal cell walls contain various ligands, such as

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hydroxyl, carboxyl, and amino groups in the chitin layer, which are responsible for fungal interactions with the environment and for the absorption and accumulation of pollutants [26, 30, 31]. By interacting with minerals, fungi play a key role in the formation of nanoparticles and metal oxide species to increase the surface area of the element in order to become more active in cleaning a pollutant [26].

The role of fungi in pesticides degradation

The increase in global food demand and the need to prevent crop losses from pests have led to the widespread use of about 2 million tons of pesticides worldwide each year [32-34]. It is assumed that almost 90% of agricultural pesticides are dispersed in the environment [32]. In fact, pesticides have been detected in the oceans, groundwater, atmosphere and soil as a result of modern agricultural practices [32, 35]. Exposure to pesticides can cause various diseases, such as cancers, teratogenic and genotoxic effects, and dysfunction of endocrine glands and nerves [36, 37]. It has been reported that fungi play a role in the degradation of a wide range of pesticides, including carbamates, organochlorines, organophosphorus, and pyrethroids [38-41]. *Aspergillus*, *Ganoderma*, *Pleurotus*, *Fusarium*, *Rhizopus*, *Cladosporium*, *Phlebia*, *Mortiella* and *Penicillium* genera can be mentioned among pesticides-destroying fungi [32]. Some of these fungi have enzymes such: versatile peroxidase, lignin peroxidase, manganese peroxidase and laccase that may play a role in bioremediation [42]. Additionally, it has also been shown that combinations of various fungi can degrade some pesticides more effectively than single strains [32, 43]. There is also a report of improved bioremediation using a combination of fungus and bacteria [44]. It is stated that *Phanerochaete chrysosporium* in combination with silicate minerals, increases pesticides bioremediation [45].

The role of fungi in the degradation of pharmaceutical active compounds

Pharmaceutical active compounds are a very important class of emerging pollutants, including diuretics, antibiotics, analgesics, sedatives, antitoxins, hormones, monoclonal antibodies, interleukins, psychiatric drugs, vaccines, etc. [46]. Pharmaceutical active compounds are released into the environment due to their stability and lack of complete metabolization in humans and animals. More than 50% of the administered pharmaceutical active compounds may not be metabolized in the user and are excreted into the environment, either in their original form or as active metabolites, through urine or feces. Other routes of these compounds into the environment include the disposal of expired drugs, agricultural activities, landfill leachatesn and urban runoff [47]. The removal of these released pharmaceutical active compounds from the environment, especially from wastewater, has been described by various authors as a very challenging task due to their high solubility, polarity, and resistance to biological degradation under environmental conditions [46-49]. The presence of pharmaceutical active compounds in the environment may cause antibiotic resistance, harm to aquatic animals, hormonal disorders and decrease the quality of drinking water [48, 50, 51]. Different research efforts have been made to remove pharmaceutical active compounds from the environment using biological methods [47, 52]. Different research has shown that different fungi and their enzymes are able to remove pharmaceutical compounds in different water systems (Table 2) [53, 54]. Fungal species have a significant advantage over bacteria in bioremediation due to their chemoheterotrophic nature, eco-friendliness, and sustainability, as well as their phylogenetic diversity and symbiotic interactions [47,55]. In the bioremediation process, fungal hyphae absorb compounds from the environment and provide the necessary enzyme systems [56]. In addition, fungi also play a role in bioremediation by producing extracellular enzymes such as laccases and peroxidases [47]. The cytochrome P450 of fungi is also involved in the processes of dehalogenation, deamination, and dealkinalization, hydroxylation, and changing the structure of pollutants [57]. Fungi play a role in bioremediation of pharmaceutical active compounds via reducing surface tension and improving molecular interactions by biosurfactants that are made up of various types of lipids, polysaccharides and protein [58]. Some fungal species with the ability to pharmaceutical active compounds are listed in Table 2.

The role of fungi in the bioremediation of heavy metals from the environment

Heavy metals are identified by three different criteria, including their density, atomic number and chemical properties [4]. Heavy metal pollution is an important environmental problem that occurs due to excessive use of agricultural inputs such as fertilizers, pesticides, and mulch, which leads to soil pollution, reduced crop production, and food quality [59]. Accumulation of high levels of metals such as zinc, copper and nickel or their ingestion in amounts greater than the necessary concentration can cause serious problems for humans, plants and animals [4]. Heavy metal toxicity is caused by various mechanisms such as: breaking fatal enzymatic functions, reacting as catalysts in the production of reactive oxygen species, disrupting ion regulation, and directly affecting DNA and protein formation [60]. Some fungi can play an important role in the bioremediation of heavy metals due to their bioabsorption, bioaccumulation, high metal concentration tolerance, and metal recovery capabilities. Some fungi can be used to recovery of many essential metals from different metal sources such as: solid mineral wastes and contaminated soils, mine tailings, electronic waste and spent catalysts [61]. It has been shown that *Aspergillus niger* is able to remove 100% of cadmium and lead from wastewater for six days. It is also reported that *Rhizopus oligosporium* is capable of removing 65% of cadmium and lead from wastewater during this period [62]. *Aspergillus* species are known for their ability to tolerate various metals including: aluminum, cadmium, lead, copper, chromium, iron, manganese, nickel and zinc [63, 64]. *Penicillium rubens* is capable of removing 98% of cadmium from polluted soil.

Table 1. List of some fungal species responsible for plastic degradation

Fungal species	Plastic Type
Aspergillus flavus, Aspergillus tubingensis	High-density polyethylene
Alternaria alternate, Aspergillus terreus, Aspergillus caespitosus, Eupenicillium hirayamae, Paecilomyces variotii, Phialophora alba	Low-density polyethylene
Aspergillus terreus, Aspergillus sydowii	Polyethylene
Zalerion maritimum	Polyethylene terephthalate
Paecilomyces farinosus, Aspergillus fumigatus	polyhydroxybutyrate
Candida guillermondii, Debaryomyces hansenii	poly-3- hydroxyalkanoates
Fusarium oxysporium, Paecilomyces lilacinus, Paecilomyces farinosus	Poly-3-hydroxybutyrate-co-3-hydroxyvalerate

Table 2. List of some fungal species responsible for pharmaceutical active compounds degradation

Fungal species	Type of pharmaceutical active compounds
Phanerochaete chrysosporium	Carbamazepine
Trametes versicolor	Diclofenac, Naproxen, Ciprofloxacin, Clarithromycin, Ketoprofen, Ibuprofen
Trametes polyzona	Tetracycline
Penicillium oxalicum	Acetylsalicylic acid, Acetaminophen, Diclofenac, Naproxen
Aspergillus niger	Naproxen
Pycnoporus sanguineus	Sulfamethoxazole, Norfloxacin, Ciprofloxacin

Penicillium simplicissimum is capable of removing about 90% of aluminum and copper from waste electrical equipment. *Cladosporium* sp. are capable of removing 74% of manganese from mine tailings [62].

The role of fungi in wastewater treatment

Wastewater treatment requires significant energy, time, and cost. It is essential to use appropriate solutions to reduce energy consumption in wastewater treatment globally. Some microorganisms can be used to remove organic, biodegradable, soluble, and nutrient-containing compounds and also colloids from wastewater. For this purpose, the wastewater is introduced into a bioreactor to be affected by bacteria, fungi, and algae. Fungi can be useful for wastewater treatment due to their diverse extracellular and intracellular enzymes, surfactant production, biosorption properties, and the ability to form symbioses. Long remediation time and slow growth of fungi may be limiting factors of this method [61]. Some fungal genera such as: *Aspergillus, Fusarium, Penicillium, Verticillium* have been investigated more than the others for bioremediation [65]. The genus Aspergillus has received special attention due to its rich species diversity and unique enzymes [61]. This genus can serve as excellent biosorbents for the removal of heavy metals, such as cadmium, copper, chromium, lead, and arsenic [61, 66-68]. *Penicillium* spp. are also very important for environmental remediation as a natural biosorbents for the reduction of heavy

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metals [69]. Many strains of this fungus can absorb zinc [61].

Discussion

Although plastic products are useful tools for society by providing convenience and comfort at low cost in daily life, the increasing amount of plastic waste is becoming a global concern as it greatly increases the pollution of the environment [21, 70]. In this article, the role of fungi in plastic degradation was mentioned. Several enzymes, such as cutinase, laccase, peroxidase, and esterase seem promising for bioremediation by fungi [21].

However, biodegradation of plastic is a slow process that requires a long time. So, the action of these enzymes needs to be studied and improved with the approach of biotechnology. Identifying optimal degradation conditions and using multiple species of fungi may help develop bioremediation approaches for plastics [21]. In the current article, the role of fungi in mineral degradation was mentioned. Fungi are an important agent of bioremediation to remove various contaminants like mineral from the environment. By interacting with different surfaces and producing diverse metabolites, fungi carry out various processes in the biosphere, such as: biotransformation, bioweathering and biomineralization, which results in the degradation of minerals [26]. For example, on the hyphal surface of Penicillium hysogenum, phosphate and carboxyl groups are major adsorption sites for lead and zinc, respectively [71]. In this article, the role of fungi in pesticide degradation was mentioned. Pesticides are used to kill unwanted plants (weeds), rodents, insects and other organisms threatening the cultured crops. It is thought that approximately 90 percent of the pesticide is not absorbed by the invading organism, but is dispersed into the environment. *Aspergillus, Fusarium, Ganoderma, Cladosporium, Rhizopus*, *Pleurotus*, and *Penicillium* are fungi that play a role in pesticide degradation [32]. In the current article, the role of fungi in degradation of pharmaceutical active compounds was mentioned. Fungi are a promising tool for clearing pharmaceutical active compounds due to their versatile metabolic capabilities. However, there are a lot of gaps to be filled in order to realize the full potential of this approach. Studies are needed to identify new fungal species with high ability to degrade pharmaceutical active compounds to increase efficiency. The development of genetic tools may enhance the engineering of fungal species with enhanced bioremediation capabilities of pharmaceutical active compounds by producing recombinant enzymes, manipulating pathways, directed evolution of proteins and fungal mutation [47]. Heavy metals can exist in the form of: hydroxides, carbonates, oxides, sulfates, sulfides, silicates, phosphates, and organic compounds [72]. Toxic heavy metals cannot be biologically decomposed when their concentration is high, and their accumulation may cause serious diseases and disorders such as diabetes, cancer, cardiovascular diseases, inflammation, neurodegeneration, and allergic responses [73, 74]. Some fungi like *Aspergillus niger* and *Trichoderma harzianum*

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can be effective in the purification of heavy metals via their ability to secrete organic acids. *Aspergillus niger* can produce citric acid and dissolve metals such as cadmium and lead, converting them into less toxic forms [75]. The use of wastewater in agriculture has increased due to its high content of major and micronutrients. However, wastewater, especially from industries, contains high concentrations of heavy metals that enter humans and animals via the food chain. So, it is better to remove these heavy metals from wastewater via low-cost technology before using them in agriculture. *Aspergillus terreus, Trichoderma viride,* and *Trichoderma longibrachiatum* have been shown to be able to remove some heavy metals from wastewater [76].

Conclusion

This review summarized research on bioremediation using filamentous fungi. The main focus is on the issue of some progress in the remediation of pharmaceutical active compounds, minerals, heavy metals, plastic, and wastewater treatment. Filamentous fungi belonging to all groups Ascomycota, Basidiomycota, and Zygomycota have good remediation potential and can be used to remove various pollutants from contaminated environments. Biomineralization, biosorption, biosurfactant production, biofouling, as well as extracellular and intracellular enzymatic processes are among the mechanisms of fungi in bioremediation

Ethical Considerations

The Ethics Committee of Jiroft University of Medical Sciences approved the study.

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Conflict of Interest

The authors declared no conflict of interest.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Authors' Contributions

N.N. was responsible for designing the review protocol, conducting the literature review, providing feedback on the manuscripts, writing the manuscript and improving the interpretation of the results. M.T.S. was responsible for writing the manuscript, assembling data, analyzing data, and interpreting analyses.

References

[1]. Narayanan M, Sameh Samir A, El-Sheekh M. A comprehensive review on the potential of microbial enzymes in multipollutant bioremediation: Mechanisms, challenges, and future prospects. J Environ Manage. 2023; 334: 117532.
[2]. Bala S, Garg D, Thirumalesh BV, Sharma M, Sridhar K, Inbaraj BS, Tripathi M. Recent strategies for bioremediation of emerging pollutants: A review for a green and sustainable environment. Toxics 2022; 10(8): 484.
[3]. Mishra P, Kiran NS, Romanholo Ferreira LF, Yadav KK, Mulla SI. New insights into the bioremediation of petroleum contaminants: A systematic review. Chemosphere 2023; 326: 138391.
[4]. Medfu Tarekegn M, Zewdu Salilih F, Ishetu AI. Microbes used as a tool for bioremediation of heavy metal from the environment. Cogent Food Agric. 2020; 6(1): 1783174.

[DOI: 10.18502/ijml.v12i2.21569]

[5]. Ayilara MS, Babalola OO. Bioremediation of environmental wastes: the role of microorganisms. Front Agron. 2023; 5: 1183691.
[6]. James TY, Stajich JE, Hittinger CT, Rokas A. Toward a fully resolved fungal tree of life. Annu Rev Microbiol. 2020; 74: 291-313.
[7]. Li Y, Steenwyk JL, Chang Y, Wang Y, James TY, Stajich JE, et al. A genome-scale phylogeny of the kingdom Fungi. Curr Biol. 2021; 31(8): 1653-665.
[8]. Rokas A. Evolution of the human pathogenic lifestyle in fungi. Nat Microbiol. 2022; 7(5): 607-19.
[9]. Blackwell M. The fungi: 1, 2, 3 ... 5.1 million species? Am J Bot. 2011; 98(3): 426-38.
[10]. Hawksworth DL, Lücking R. Fungal diversity revisited: 2.2 to 3.8 million species. Microbiol Spectr. 2017; 5(4): 79-95
[11]. Kamali M, Seyyedi SS, Taheri Sarvtin M. A Study on the Presence of Aflatoxin M1 in Cow's Milk in Jiroft. Int J Med Lab. 2021; 8(2): 147-53.
[12]. Kamali M, Taheri Sarvtin M. A survey on airborne fungal spores in indoor air and outdoor air of Babol city. Journal of Jiroft University of Medical Sciences 2015; *2*(1): 116-30.
[13]. Mehni S, Zahrani, ST, Sarvtin MT, Mojab F, Mirzaei M, Vazirnasab H. Therapeutic effects of bunium perscicum boiss (Black Zira) on candida albicans vaginitis. Biom Pharmacol. 2015; 8(2): 1103-109.
[14]. Kamali M, Taheri Sarvtin M. Fungal colonization of wood and wood products inside the buildings of Sari, northern Iran. SAJEB. 2016; 6(3): 101-104.
[15]. Taheri Sarvtin M, Hajheydari Z, Hedayati M. A review on the role of fungi in atopic dermatitis. J Maz Univ Med. 2012; 22(87): 115-37.
[16]. Afsarian MH, Shokohi T, Arzanlou M, Taheri Sarvtin M, Badali, H. Phaeohyphomycosis due to dematiaceous fungi a review of the literature. J Maz Univ Med. 2012; 22(92): 100-126.
[17]. Taheri Sarvtin M. A Review of the role of indoor fungi in sick building syndrome. Int J Med Lab. 2023; 10(3):196-207.
[18]. Taheri Sarvtin M, Kamali, M. A review of the latest findings of candida colonization and candidiasis in patients with psoriasis and its management. Int J Med Lab. 2023; 10(3): 187-95.
[19]. Kamali M, Sarvtin MT. Diversity and distribution patterns of culturable airborne fungi in Jiroft city. Int J Med Lab. 2023; 10 (4): 340-46.
[20]. Sarvtin MT, Abastabar M. Malassezia species in dermatology: A review. Dermatol Cosmetic. 2015; 6(1): 58-74.
[21]. Viel T, Manfra L, Zupo V, Libralato G, Cocca M, Costantini M. Biodegradation of plastics induced by marine organisms: future perspectives for bioremediation approaches. Polymers (Basel). 2023; 15(12): 2673.
[22]. Ameen F, Moslem M, Hadi S, Al-Sabri AE. Biodegradation of low density polyethylene (LDPE) by Mangrove fungi from the red sea coast. Prog Rubber Plast Recycl. Technol. 2015; 31(2): 125-43.
[23]. Mehra R, Muschiol J, Meyer AS, Kepp KP. A structural-chemical explanation of fungal laccase activity. Scientific Reports 2018; 8(1): 17285.
[24]. Zhang J, Gao D, Li Q, Zhao Y, Li L, Lin H, et al. Biodegradation of polyethylene microplastic particles by the fungus Aspergillus flavus from the guts of wax moth Galleria mellonella. Sci Total Environ. 2020; 704: 135931.
[25]. Santacruz-Juárez E, Buendia-Corona RE, Ramírez RE, Sánchez C. Fungal enzymes for the degradation of polyethylene: Molecular docking simulation and biodegradation pathway proposal. J Hazard Mater. 2021; 411:125118.
[26]. Muksy R, Kolo K, Abdullah SM. Bacterial and fungal-mineral interactions and their application in bioremediation–A review. Ecol Eng. 2023; 24(5): 1-13.
[27]. Brandl H. Metal-microbe-interactions and their biotechnological applications for mineral waste treatment. Recent Res Dev Microbiol. 2002; 6: 571-84.
[28]. Kushwaha A, Hans N, Kumar S, Rani R. A critical review on speciation, mobilization and toxicity of lead in soil-microbe-plant system and bioremediation strategies. Ecotoxicol Environ Saf. 2018;147: 1035-1045.
[29]. Tabak HH, Lens P, Van Hullebusch ED, Dejonghe W. Developments in bioremediation of soils and sediments polluted with metals and radionuclides–1. Microbial processes and mechanisms affecting bioremediation of metal contamination and influencing metal toxicity and transport. Rev Environ Sci Biotechnol. 2005; 4: 115–156.
[30]. Göhre V, Paszkowski U. Contribution of the arbuscular mycorrhizal symbiosis to heavy metal phytoremediation. Planta. 2006; 223(6): 1115-122.
[31]. Rosén K, Weiliang Z, Mårtensson A. Arbuscular mycorrhizal fungi mediated uptake of 137Cs in leek and ryegrass. Sci Total Environ. 2005; 338(3): 283-90.
[32]. Vaksmaa A, Guerrero-Cruz S, Ghosh P, Zeghal E, Hernando-Morales V, Niemann H. Role of fungi in bioremediation of emerging pollutants. Front Mar Sci. 2023; 10: 1070905.
[33]. Sharma A, Kumar V, Shahzad B, Tanveer M, Sidhu GPS, Handa N, et al. Worldwide pesticide usage and its impacts on ecosystem. SN Appl Sci. 2019; 1: 1446.
[34]. Lykogianni M, Bempelou E, Karamaouna F, Aliferis KA. Do pesticides promote or hinder sustainability in agriculture? The challenge of sustainable use of pesticides in modern agriculture. Sci Total Environ. 2021; 795: 148625.
[35]. Wołejko E, Jabłońska-Trypuć A, Wydro U, Butarewicz A, Łozowicka B. Soil biological activity as an indicator of soil pollution with pesticides–a review. Appl Soil Ecol. 2020; 147: 103356

[36]. Kim KH, Kabir E, Jahan SA. Exposure to pesticides and the associated human health effects. Sci Total Environ. 2017; 575: 525-35.
[37]. Shah ZU, Parveen S. Pesticides pollution and risk assessment of river Ganga: A review. Heliyon. 2021; 7(8): 7726.
[38]. Maqbool Z, Hussain S, Imran M, Mahmood F, Shahzad T, Ahmed Z, et al. Perspectives of using fungi as bioresource for bioremediation of pesticides in the environment: A critical review. Environ Sci pollut Res. 2016; 23: 16904-16925.
[39]. Bokade P, Purohit HJ, Bajaj A. Myco-remediation of Chlorinated Pesticides: insights into fungal metabolic system. Indian J Microbiol. 2021; 61(3): 237-49.
[40]. Bose S, Kumar PS, Vo DVN, Rajamohan N, Saravanan R. Microbial degradation of recalcitrant pesticides: a review. Environ Chem Lett. 2021; 19: 3209-228.
[41]. Kumar M, Yadav AN, Saxena R, Paul D, Tomar RS. Biodiversity of pesticides degrading microbial communities and their environmental impact. Biocatalysis Agric. Biotechnol. 2021; 31: 101883.
[42]. Zhuo R, Fan F. A comprehensive insight into the application of white rot fungi and their lignocellulolytic enzymes in the removal of organic pollutants. Sci Total Environ. 2021; 778: 146132.
[43]. Nyakundi W, Magoma G, Ochora J, Nyende A. Biodegradation of diazinon and methomyl pesticides by white rot fungi from selected horticultural farms in rift valley and central Kenya. J Appl Technol Environ Sanit. 2011; 1 (2): 107–124.
[44]. Knudsen BE, Ellegaard-Jensen L, Albers CN, Rosendahl S, Aamand J. Fungal hyphae stimulate bacterial degradation of 2,6-dichlorobenzamide (BAM). Environ. Pollut. 2013; 181: 122-27.
[45]. Wang C, Yu L, Zhang Z, Wang B, Sun H. Tourmaline combined with Phanerochaete chrysosporium to remediate agricultural soil contaminated with PAHs and OCPs. J Hazard Mater. 2014; 264: 439-48.
[46]. Rodrigues JA, Silva S, Cardoso VV, Benoliel MJ, Almeida CM. Different approaches for estimation of the expanded uncertainty of an analytical method developed for determining pharmaceutical active compounds in wastewater using solid-phase extraction and a liquid chromatography coupled with tandem mass spectrometry method. Anal Methods. 2023; 15(1): 109-123.
[47]. Amobonye A, Aruwa CE, Aransiola S, Omame J, Alabi TD, Lalung J. The potential of fungi in the bioremediation of pharmaceutically active compounds: A comprehensive review. Front Microbiol. 2023; 14: 1207792.
[48]. Papagiannaki D, Belay MH, Gonçalves NP, Robotti E, Bianco-Prevot A, Binetti R, et al. From monitoring to treatment, how to improve water quality: the pharmaceuticals case. Chem Engin J Adv. 2022; 10: 100245–100217.
[49]. Christensen ER, Wang Y, Huo J, Li A. Properties and fate and transport of persistent and mobile polar organic water pollutants: A review. J Environ Chem Eng. 2022; 107201: 1-14.
[50]. Dos Santos CR, Arcanjo GS, de Souza Santos LV, Koch K, Amaral MCS. Aquatic concentration and risk assessment of pharmaceutically active compounds in the environment. Environ Pollut. 2021; 290: 118049.
[51]. He P, Wu J, Peng J, Wei L, Zhang L, Zhou Q, Wu Z. Pharmaceuticals in drinking water sources and tap water in a city in the middle reaches of the Yangtze River: occurrence, spatiotemporal distribution, and risk assessment. Environ Sci Pollut Res Int. 2022; 29(2): 2365-374.
[52]. Bilal M, Adeel M, Rasheed T, Zhao Y, Iqbal HM. Emerging contaminants of high concern and their enzyme-assisted biodegradation–a review. Environ Int. 2019; 124: 336-53.
[53]. Narayanan M, El-Sheekh M, Ma Y, Pugazhendhi A, Natarajan D, Kandasamy G, et al. Current status of microbes involved in the degradation of pharmaceutical and personal care products (PPCPs) pollutants in the aquatic ecosystem. Environ Pollut. 2022; 300: 118922.
[54]. Ferrando-Climent L, Cruz-Morató C, Marco-Urrea E, Vicent T, Sarrà M, Rodriguez-Mozaz S, et al. Non conventional biological treatment based on Trametes versicolor for the elimination of recalcitrant anticancer drugs in hospital wastewater. Chemosphere. 2015; 136: 9-19.
[55]. Ferreira JA, Varjani S, Taherzadeh MJ. A critical review on the ubiquitous role of filamentous fungi in pollution mitigation. Curr Pollut Rep. 6: 295–309.
[56]. Gómez-Toribio V, García-Martín AB, Martínez MJ, Martínez AT, Guillén F. Enhancing the production of hydroxyl radicals by Pleurotus eryngii via quinone redox cycling for pollutant removal. Appl Environ Microbiol. 2009; 75(12): 3954-962.
[57]. Manasfi R, Chiron S, Montemurro N, Perez S, Brienza M. Biodegradation of fluoroquinolone antibiotics and the climbazole fungicide by Trichoderma species. Environ Sci Pollut Res Int. 2020; 27(18): 23331-3341.
[58]. Olicón-Hernández DR, González-López J, Aranda E. Overview on the biochemical potential of filamentous fungi to degrade pharmaceutical compounds. Front Microbiol. 2017; 8: 1792.
[59]. Su C. A review on heavy metal contamination in the soil worldwide: Situation, impact and remediation techniques. Environ Skep Crit. 2014; 3(2): 24.
[60]. Gauthier PT, Norwood WP, Prepas EE, Pyle GG. Metal-PAH mixtures in the aquatic environment: A review of co-toxic mechanisms leading to more-

[DOI: 10.18502/ijml.v12i2.21569]

than-additive outcomes. Aquat Toxicol. 2014; 154: 253-69.
[61]. Ghosh S, Rusyn I, Dmytruk OV, Dmytruk KV, Onyeaka H, Gryzenhout M, et al. Filamentous fungi for sustainable remediation of pharmaceutical compounds, heavy metal and oil hydrocarbons. Front Bioeng Biotechnol. 2023; 11: 1106973.
[62]. Ghyadh BA, Al-Ashoor A, and Ibrahim ZM. Biotechnology of waste water treatment with fungi (Aspergillus niger and Rhizopus oligosporium). Plant Arch. 2019; 19: 1546-549.
[63]. Dusengemungu L, Kasali G, Gwanama C, Mubemba B. Overview of fungal bioleaching of metals. Environ Adv. 2021; 5: 100083.
[64]. Naveen Kumar K, Prakash J. Bioremoval of different heavy metals in industrial effluent by the resistant fungal strain Aspergillus niger. Nat Environ Pollut Technol. 2021; 20: 4.
[65]. Olicón-Hernández DR, González-López J, Aranda E. Overview on the biochemical potential of filamentous fungi to degrade pharmaceutical compounds. Front Microbiol. 2017; 8: 1792.
[66]. Barros L. M Macedo GR, Duarte MML, Silva EP, Lobato AKCL. Biosorption of cadmium using the fungus Aspergillus niger. Braz J Chem Eng. 2003; 20: 229-39.
[67]. Cernansky S, Urik M, Sevc J, Littera P, Hiller E. Biosorption of arsenic and cadmium from aqueous solutions. Afr J Biotechnol. 2007; 6: 1932-934.
[68]. Mukherjee A, Das D, Kumar Mondal S, Biswas R, Kumar Das T, Boujedaini N. Tolerance of arsenate-induced stress in Aspergillus niger, a possible candidate for bioremediation. Ecotoxicol Environ Saf. 2010; 73(2): 172-82.
[69]. Fan T, Liu YG, Feng BY, Zeng GM, Yang CP, Zhou M, et al. Biosorption of cadmium (II), zinc (II) and lead (II) by Penicillium simplicissimum: Isotherms, kinetics and thermodynamics. J Hazard Mater. 160: 655-61.
[70]. Evode N, Qamar SA, Bilal M, Barceló D, Iqbal HM. Plastic waste and its management strategies for environmental sustainability. Case Studies Chem Environ Engineering. 2021; 4: 100142.
[71]. Fomina M, Alexander IJ, Hillier S, Gadd G. Zinc phosphate and pyromorphite solubilization by soil plant-symbiotic fungi. Geomicrobiology 2004; 21(5): 351-66.
[72]. Singh R, Gautam N, Mishra A, Gupta R. Heavy metals and living systems: An overview. Indian J Pharmacol. 2011; 43(3): 246-53.
[73]. Jackson RB, Carpenter SR, Dahm CN, McKnight DM, Naiman RJ, Postel SL, et al. Water in a changing world. Ecol Appl. 2001; 11(4): 1027-1045.
[74]. Haidar Z, Fatema K, Shoily SS, Sajib AA. Disease-associated metabolic pathways affected by heavy metals and metalloid. Toxicol Rep. 2023; 10:554-70.
[75]. Dinakarkumar Y, Gnanasekaran R, Reddy GK, Vasu V, Balamurugan P, Murali, G. Fungal bioremediation: An overview of the mechanisms, applications and future perspectives. Environ Chem Ecotoxicol. 2024; 6: 293-302
[76]. Joshi PK, Swarup A, Maheshwari S, Kumar R, Singh N. Bioremediation of heavy metals in liquid media through fungi isolated from contaminated sources. Indian J Microbiol. 2011; 51(4): 482-87.

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