Mycoremediation of pesticide-contaminated soil: A review

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Abstract. Pesticide contamination in soil presents significant environmental and health risks due to toxic residues. Traditional physical and chemical remediation methods are often expensive, ineffective at low concentrations, and generate toxic by-products. Mycoremediation, utilizing fungi for bioremediation, provides a cost-effective, eco-friendly, and efficient solution. This review explores fungi for remediating pesticide and herbicide pollutants. Indigenous fungi, especially Aspergillus and Penicillium species, show substantial potential in bioremediating xenobiotics like organochlorine and organophosphorus pesticides due to their versatile enzymatic systems. These fungi degrade pesticides into less toxic metabolites or entirely mineralize them within days, using the compounds for carbon, sulfur, and phosphorus. Fungi possess specific gene clusters for pesticide utilization, making them valuable for managing contamination from pesticides such as glyphosate. Mycoremediation offers a promising alternative, as fungi can degrade and detoxify pesticides through biochemical mechanisms like oxidation and reduction reactions. Using indigenous fungi in bioremediation reduces pesticide toxicity, supports sustainable agriculture, maintains soil fertility, and prevents biomagnification. This review examines recent studies on fungi in degrading pesticide-contaminated land and provides scientific evidence supporting mycoremediation as a solution for soil contamination.

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1 Introduction

The agricultural sector holds great significance for the State, as it plays a vital role in the economy [1], [2], [3]. The rapid growth of the population has a direct impact on enhancing the quality of sustainable agriculture. To improve the quality of agricultural products, it is essential to have adequate facilities and infrastructure, such as the use of fertilizers, agricultural tools, and chemicals like pesticides and herbicides [4], [5].

The global usage of pesticides has increased to 3.5 million tons [6], primarily to increase food production and protect against crop losses. However, excessive use of pesticides can have detrimental effects on the environment. Pesticide residues can be found in the soil, water, and air, causing pollution in surrounding areas [7], [8], [9]. Furthermore, exposure to pesticide residues can have toxic effects on human health, leading to both acute and chronic health issues [10], [11].

The development of processes to restore polluted environments is necessary to address land pollution caused by a variety of chemicals and heavy metals used to combat soil and water contamination [12]. While there are currently physical and chemical methods available to remove pollutants, these methods are often costly, produce toxic by-products, and are ineffective at low concentrations [13]. To overcome these limitations, an in-situ remediation process of pollutants is required [14], [15]. Mycoremediation offers a cost-effective, environmentally friendly, and effective solution to combat land pollution problems that continue to rise due to the use of chemicals and water pollution [16]. In the remediation process, the ideal mold features strong fungal growth, extensive hyphae network, extracellular ligninolytic production, high surface area to volume ratio, resistance to heavy metals, ability to adapt to pH and temperature fluctuations, and the presence of metal binding proteins [17], [18].

Indigenous fungi are crucial for pesticide degradation, providing a sustainable solution to environmental issues caused by these toxins. Fungi, particularly Aspergillus and Penicillium, exhibit significant potential in bioremediating xenobiotics like organochlorine and organophosphorus pesticides due to their versatile enzymatic systems. These fungi, prevalent in pesticide-contaminated soils, degrade these compounds into less toxic metabolites or completely mineralize them within days [19]. Their metabolic abilities position fungi as prime degraders of persistent organic matter, with their mycoremediation role extensively studied in terrestrial and aquatic ecosystems [20]. Research indicates fungi such as Aspergillus niger, Penicillium, and Fusarium effectively degrade chlorinated pesticides, utilizing these compounds for carbon, sulfur, and phosphorus, aiding in detoxification [21]. Fungi like Aspergillus fumigatus possess specific gene clusters for pesticide utilization, making them valuable for managing contamination from pesticides like glyphosate [22].

Fungi in bioremediation, known as mycoremediation, offer a cost-effective and eco-friendly alternative to traditional methods for cleaning pesticide-contaminated soils and water. This method is promising due to its ability to degrade and detoxify pesticides through biochemical mechanisms like oxidation and reduction reactions [23], [24]. A variety of microbial species, including fungi, with diverse metabolic pathways, significantly contribute to the natural degradation of hazardous substances [25]. Using indigenous fungi in bioremediation reduces pesticide toxicity in the environment, enhances sustainable agriculture, maintains soil fertility, and prevents biomagnification [26], [27]. Thus, indigenous fungi in bioremediation provide an effective solution for reducing pesticide pollution, promoting a healthier and more sustainable environment. The objective of this review is to examine the investigation the latest studi of fungi in degrading land polluted with pesticides and to present scientific evidence endorsing the application of mycoremediation as a remedy for soil contamination issues.

2 Material and Methods

An article reviews titled " MYCOREMEDIATION of PESTICIDE-CONTAMINATED SOIL " was conducted through a comprehensive literature review. In order to prepare for this review, several research questions were developed based on the findings of previous studies (Abdel-Latif et al., 2020; N. Akhtar & Mannan, 2020; Mani & Kumar, 2014; A. Patel et al., 2021a). The literature search was conducted online using various sources, including ScienceDirect, Springer, Google Scholar, and Researchgate. The primary goal of this review is to provide a comprehensive overview of the literature on bioremediation of pesticide-contaminated soils and to identify areas for future research. Additionally, the review aims to provide guidance to researchers on selecting the most effective bioremediation techniques for specific conditions of pesticide-contaminated soils.

3 Results and Discussion

Mycoremediation, the use of fungi to remediate contaminated environments, has garnered attention for its eco-friendly and cost-effective nature. Studies highlight its efficacy against pollutants such as heavy metals, organic contaminants, and pharmaceuticals (Figure 1). For example, *Pleurotus spp*. can enhance plant growth on metal-contaminated soils by providing nutrients and reducing metal toxicity, tolerating metals like cobalt and copper while showing inhibited growth with nickel. Fungal-bacterial co-cultures enhance the mineralization of polycyclic aromatic hydrocarbons (PAHs) through complementary enzymatic activities [1].

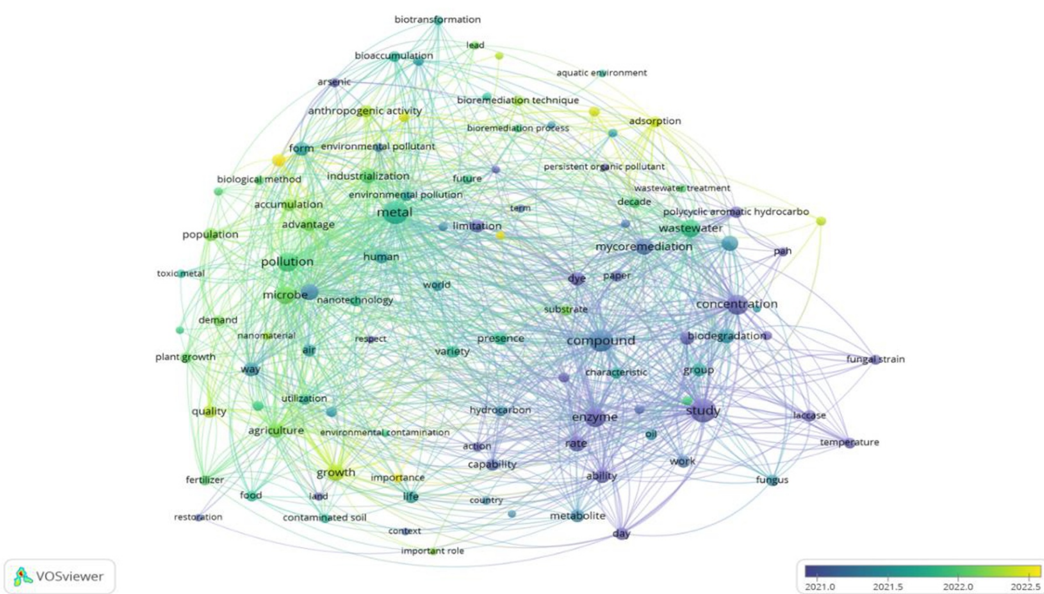

Fig. 1. Bibliometric data about Pesticide Mycoremediation

3.1 Pesticides and their impact

Pesticides, such as herbicides, insecticides, fungicides, and rodenticides, are a group of chemicals used in agriculture and industry to control pests [2], [3]. Pesticides are classified into different categories based on their chemical composition, mechanism of action, toxicity, and application method [4], [5]. One way to classify pesticides is based on their chemical composition, which can reveal synergistic interactions between activity, structure, degradation potential, and toxicity. Pesticides are generally categorized into four groups based on their chemical composition: organochlorines, organophosphates, carbamates, and pyrethroids. Organochlorine pesticides, such as aldrin, endrin, chlordane, heptachlor, dieldrin, The classification of pesticides has been studied extensively, and future researchers can utilize this knowledge to conduct mold-mediated remediation by examining the composition of the compounds present (Figure 2). This is because, during degradation tests, only certain active compounds can be grouped based on factors such as toxicity, chemical content, market use, structure, and degradation potential.

Fig. 2. Pesticide classification

Table 1. Pesticide Impacts

Pesticide	Pesticide impact	References
Malathion	The exposure of malathion within granulosa cells can have toxic effects, leading to histological changes in animals and causing damage to ecosystems.	[6], [7], [8]

Organochlorine	This substance poses significant risks to human health due to its carcinogenic properties and toxic effects, as well as causing severe ecological damage	
Lead (Pb)	Exposure to lead (Pb) can result in poisoning in humans	[9]
Karbamat	Harmful effects on human nerve tissue and lung damage can result	[10], [11]
Piretroid	In humans, it can cause harmful effects and physiological and histological changes in animals	[12], [13]
Organophosphate	It can have harmful effects on mammals, such as humans and birds	[14]
Benzo-α-pyrene and phenanthrene	The toxicity of PAHs and PACs can lead to impairments in endocrine function, microbial resistance, and disruptions in aquatic ecosystems.	[15]
Hg	The negative effects of mercury pollution have been widely documented, posing a serious threat to various living organisms and ecosystems, making it a pressing environmental issue.	[16]
Cadmium	Cadmium can have detrimental effects on soil	[17]
Zn	The presence of high levels of Zn content has been linked to a decrease in high-density lipoprotein levels and immune function.	[18]

Previous studies showed that pesticide residues have lasting negative impacts on the environment. To enhance the efficacy and consistency of the composition, several substances are included. These include non-ionic surfactants like alkylphenols, ethoxylates (APEO), alcohol ethoxylates (AEO), alkylamine ethoxylates (ANEO), organosilicone polyethoxylates, fatty amine polyethoxylates, and cosolvents such as N-methyl-2-pyrrolidone (NMP), which enhance the solubility of the active ingredient and provide protection. Active chemicals in pesticides have several roles such as spreading, controlling foam, adding colour, and preventing drift. These functions impact the physical and chemical features of pesticide products [19], [20], [21], [22]. Active chemicals are crucial elements in pesticide products that serve as dispersants, anti-foam agents, colourants, and drift inhibitors, modifying the physicochemical characteristics of these products [20]. Pesticides' residues can contribute to increased toxicity in addition to the toxicity of their active components. POEA, surfactants used in glyphosate-based herbicides, have potential toxicity[23]. More harm can come from commercial pesticide mixtures than from their individual active ingredients. Studies on bifenthrin, fipronil, carbaryl, malathion, imidacloprid, azoxystrobin, and tebuconazole show this[24], [25]. Herbicides like 2,4-D, aminopyralid, and dicamba are known to hurt both plants and animals. These effects include cytotoxic, genotoxic, mutagenic, and histopathological effects [26], [27].

3.2 The Role of Fungi in Pesticide Remediation

Environmental pollution by pesticides and herbicides is a major issue. Postharvest crops are often improved with pesticides. These chemicals can cause neurological damage due to excessive exposure [25], inhibited fruit development in plants [28], and histological and physiological effects on animals. Herbicides can manage weeds and boost crop yields [23], but their excessive usage can affect soil function and animal and environmental health. PPO activity prevents weed dehydration and necrosis during chlorophyll production[19]. As ecological decomposers, fungi are crucial to Earth. In recent decades, scientists have investigated fungal biogeochemistry under environmental stress. Fungi cooperate with other microorganisms, especially plants, to restore damaged soil, water, and air and can be utilized in designing nanobiotechnology tools [29]. Biocatalytic activity makes these prospective bacteria the principal bioremediation mediators[30]. Mycoremediation uses fungus to remove pesticide residues and heavy metals from water and soil [31]. Adding *F. pinicola* degraded DDT insecticides by 61%. Synergistic DDT degradation produces DDE, DDD, and DDMU. DDT degradation involves reductive dechlorination, dehydrogenation, and de-chlorination [32]. Bioaugmentation by *Aspergillus* spp. degrades the pyrethroid pesticide group, restoring soil faster [33], [34]. Another research found that *Aspergillus* sp. may recover chlorpyrifos, methyl parathion, and profenofos residues in 24 h. Meanwhile, *Lentinula edodes* species can improve biopurification systems for wastewater contaminated with difenoconazole and pendimethalin pesticides [35], [36]. *Fusarium* sp., *Aspergillus* sp., *Pleurotus ostreatus*, and basidiomycetes can quickly degrade herbicide residues containing glyphosphate, atrazine, desethylatrazine, and desisopropylatrazine. Since fungal strains can remediate pesticide- and herbicide-contaminated land, several researchers have studied them.

Fungi are highly effective in remediating polluted environments due to their ability to activate breakdown enzymes. These enzymatic systems enable them to clean pesticide-contaminated soils (Figure 3). Filamentous fungi, such as *Aspergillus* and *Penicillium*, can degrade endosulfan, lindane, chlorpyrifos, and methyl parathion within days. As a result, they are ideal for soil remediation [37]. Fungi like *Aspergillus niger*, *B. antennata, F. graminearum, P. digitatum, R. stolonifer,* and *T. viride* can degrade diazinon, with B. antennata reducing its concentration by 83.88% in just 10 days [38]. Fungi use pesticides as a source of carbon to bioremediate them into safer compounds. Fungal involvement in the biogeochemical cycle and their ability to handle xenobiotics make them more effective in degrading pesticides like cypermethrin and its dangerous metabolite 3-phenoxy benzoic acid than bacteria. Indigenous bacteria and fungi can also break down carbaryl, monocrotophos, and malathion, with Bacillus sp being the most active. Fungal bioremediation is a cost-efficient and eco-friendly solution for remediating pesticide-contaminated soils, protecting both human and environmental health [39].

Fig. 3. Depicts how fungi degrade pesticides in soil.

Table 3. Pesticide-Degrading Fungi

Species	Pesticides	Methods	Results	Referensi
Fomitopsis pinicola	DDT	Biodegradation and biotransformation of DDT into DDD, DDE, and DDMU	*F. pinicola,* a fungus, biodegrades about 61% of DDT	[40]
Aspergillus sp	Pyrethroid	Bioaugmentasi	Utilizing fungal augmentation can expedite the process of restoring soil contaminated with pyrethroids	[41], [42], [43]
Aspergillus section *Flavi* strains	Chlorpyros	Biodegradation	The tested conditions demonstrated rapid adaptation with the emergence of significantly reduced lag phase.	[44]
Aspergillus sydowii CBMAI 935	Chlorpyros metil parathion and profenofos	Biodegradation → chlorpyros dan biotransformation → metil parathion and profenofos	*Aspergillus sydowii CBMAI* 935 recovered from the sea, can serve as a potential biocatalyst for bioremediation applications in the future.	[15], [45]
Shewanella sp. BT05	Klorpirifos	Biodegradastion	The rapid degradation of CPs by *Shewanella* sp. BT05 is clearly exhibited, with a significant decrease of 94.3% within just 24 hours.	[46]
Lentinula edodes	Difenoconazole dan pendimethalin.	Biodegradation in liquid medium	The efficiency of biopurification systems containing contaminated wastewater can be improved by the use of *Lentinula edodes* strain.	[47]

3.3 Metabolic Pathway Pesticide Biodegradation

Fungi detoxify and convert pesticides through various metabolic pathways. For example, Cunninghamella elegans uses cytochrome P450 and flavin monooxygenase enzymes to oxidize and hydrolyze diazinon into diazoxon and pyrimidinol[48]. *Trichoderma lixii* and *Talaromyces pinophilus* degrade fluoranthene by upregulating ligninolytic enzymes and initiating degradation at specific ring locations via the ß-Ketoadipate pathway[49]. *Fusarium oxysporum, Paecilomyces variotii*, and *Trichoderma viride* can biodegrade pesticides like terbuthylazine, difenoconazole, and pendimethalin up to 100%, utilizing diverse metabolic routes in different media [50]. Fungi also assist bacteria in nutrient dispersion and mobilization, enhancing biotransformation of substances like hexachlorocyclohexane (HCH) by co-metabolizing bacteria[51]. Genomic, proteomic, and metabolomics studies have illuminated the population dynamics and metabolic pathways involved in pesticide degradation, facilitating better strategies for microbial degradation[52]. *Trichoderma viridae* and *Aspergillus niger* break C-P and C-N bonds to release inorganic phosphate and other metabolites for further breakdown[53]. Fungi's complex metabolic pathways and enzymatic interactions with other microorganisms make them effective bioremediators[54]. Their enzymatic machinery facilitates pesticide biodegradation, with enzymes breaking down harmful compounds like organochlorine and organophosphate insecticides. Fusarium equiseti and Trichoderma atroviride transfer nutrients and produce enzymes such as haloalkane dehalogenase and TaPon1-like hydrolase to enhance HCH and DDVP biotransformation, crucial for pesticide degradation[55]. Fungi like Aspergillus and Penicillium, due to their high tolerance and enzymatic activity, can degrade organochlorine and organophosphorus insecticides into less harmful metabolites or achieve total mineralization [37]

Hydrolysis, oxidation, and reduction reactions disintegrate pesticides into intermediate chemicals. Mucor racemosus and Mortierella sp. digest pesticides such as dieldrin and endosulfan, resulting in the production of intermediate metabolites like aldrin trans-diol and endosulfan diol. These metabolites are then converted into safer compounds[56]. *Fusarium oxysporum* and *Paecilomyces variotii* biodegrade herbicides like terbuthylazine and pendimethalin in biopurification systems[50]. The use of advanced omics techniques has elucidated the genetic and proteomic basis of these metabolic pathways, enabling the production of genetically modified fungus with improved degradation capabilities [52], [54]. Fungi are valuable bioremediation agents due to their diverse metabolic pathways and enzymatic activities, which facilitate the biodegradation of contaminants [38].

3.4 Mycoremediation Strategies

Several approaches are utilized in the detoxification process of land contaminated with pesticide residues, including biosorption, biomineralization, bioaccumulation, biointracellular and extracellular precipitation, and biotransformation, which involve various signaling pathways [57].

Biosorption, a common mechanism observed in microorganisms, occurs through ionic interactions between adsorbing materials, such as cell wall components or extracellular polymeric substances (EPS), and dead microbial biomass, which is a non-metabolic process. In this process, pollutants are bound to the cell walls of fungi, yeast, algae, and bacteria, with the charge originating from the cell walls. The binding process is facilitated by metal ions, and environmental factors, such as the availability of metal species, pH, and temperature, play significant roles[58]. Pollutants, such as benzo-a-pyrene, phenanthrene, lead, cadmium, tin, nickel, and uranium, can be degraded through a biosorption process involving *Rhodotula mucilaginosa, Aspergillus sp., Pleurotus ostreatus ISS-1*, and *Cladosporium sp. strain F1*[59], [60], [61], [62], [63].

Biomineralization is a mycoremediation mechanism that converts dissolved pollutants into a solid, environmentally safe form. It occurs intracellularly and involves the re-absorption of pollutants into the environment in solid and extracellular form via extracellular polymers (EPS) produced by cells. Biomineralization operates through supramolecular mechanisms based on multi-ionic and kinetic regulation through stress control [64], [65].

Microbial strains can also be used to reduce pollutants without damaging the environment through biological mechanisms. This process involves the conversion of toxic pollutants into metabolites that are safe for the environment. Biostimulation, which involves providing nutrients in gas, solid, or liquid form to polluted land, and bioaugmentation, which involves adding microbes to the environment to degrade pollutants, are two techniques used in this process. Intrinsic remediation, which involves the collection of microbes on polluted land and the availability of nutrients to support the activity of microorganisms in reducing pollutants, is another technique that can be employed.

3.5 The Prospect of Mycoremediation in Cleansing Contaminated Land

Soil contamination has become an international issue due to extensive use of chemicals in agriculture[5], [25], [66]. The primary pollutants stem from pesticides and herbicides, which are toxic to organisms and harmful to the environment[67]. These chemicals not only dry out land but also adversely affect air quality, as droplets may evaporate before reaching targets and soil particles can be windborne[68] (Hassan et al., 2020b). Pesticide residue contamination from agricultural sources poses significant environmental risks and leaves behind harmful metabolites. Numerous pesticides and herbicides are hydrophobic contaminants that, by adsorbing soil particles, can migrate to aquatic environments, threatening these ecosystems[69].

Owing to the pervasive and extensive use of pesticides in agriculture, soil pesticide residues can serve as useful indicators of the spatial distribution of soil properties. In a study that spanned approximately four years, 96 soil samples were collected from 71 adjacent fields after the last application of atrazine. The results showed a significant influence of soil texture and a decline in soil quality[21], [29], [35], [70].

Biological remediation technologies encompass a range of techniques, such as bioremediation, phytoremediation, bioventing, bioleaching of agricultural land, use of bioreactors, composting, bioaugmentation, and biostimulation [31], [68], [71], [72]. Among these, bioremediation technology is the most widely used due to its advantages over physico-chemical methods. Bioremediation takes place naturally through processes such as siderophores, organic acids, biosurfactant production, biomethylation, and redox processes [13], [95].

In Mycoremediation process, fungal mycelia play a significant role in the bioremediation process. The fungal decomposition process is carried out by mycelium, which secretes extracellular enzymes and acids that break down lignin and cellulose (i.e., the building blocks of plant fiber) and help in dissolving and complexing metal cations [75], [76], [77]. Studies on mycoremediation have expanded the use of different fungi to extract pesticides and herbicides from soil. Fungi can be unicellular or multicellular, have thalloid or filamentous structures, and reproduce asexually and sexually by the production of spores and gametes, respectively[78]. The effectiveness of mycoremediation depends on the ability of fungal species to target specific trace metals in the substrate. Most fungi produce extracellular enzymes and organic acids that break down complex substances into solutes for fungal nutrition and are considered efficient recyclers in nature [79]. Mycoremediation is a valuable technique for the remediation of land contaminated with pollutants resulting from the use of pesticide and herbicide residues. This is due to its numerous advantages over physico-chemical processes that utilize biological methods, including its environmental friendliness and the ability to be applied continuously.

4 Conclusion

This article review presents data on the use of fungi in the remediation of pesticide and herbicide pollutants. Excessive use of pesticides in agriculture can have detrimental effects on the environment and human health. Mycoremediation offers a cost-effective, eco-friendly, and effective solution to combat land pollution caused by chemicals. Indigenous fungi, particularly Aspergillus and Penicillium, exhibit significant potential in bioremediating xenobiotics like organochlorine and organophosphorus pesticides. Fungi degrade these compounds into less toxic metabolites or completely mineralize them within days. Studies highlight the efficacy of mycoremediation against pollutants such as heavy metals, organic contaminants, and pharmaceuticals. Pesticides are classified based on their chemical composition, which can reveal synergistic interactions between activity, structure, degradation potential, and toxicity. The objective of this review is to examine the latest studies of fungi in degrading land polluted with pesticides and to present scientific evidence endorsing the application of mycoremediation as a remedy for soil contamination issues.

References

1. G. Afriyanti, A. Mariya, C. Natalia, S. Nispuana, M. Farhan Wijaya, and M. Y. Phalepi, The role ff the agricultural sector on economic growth in Indonesia. Indonesian J. of Multidisciplin. Sci. (IJoMS) **2**, 167 (2023)
2. I. Mukhlis and Ö. S. Gürçam, The role of agricultural sector in food security and poverty alleviation in Indonesia and Turkey. Asian J. of Agricul. Extens. Eco. & Socio. 430 (2022)
3. A. Ashok and D. S. Kumar, Laboratory scale bioreactor studies on the production of L-asparaginase using Rhizopus microsporus IBBL-2 and Trichosporon asahii IBBLA1. Biocatal Agric Biotechnol. **34**, (2021)
4. S. B. Esparza-Naranjo et al., Potential for the biodegradation of atrazine using leaf Litter fungi from a subtropical protection area. Curr. Microbiol. **78**, 358 (2021)
5. J.V. Rohit, R.K. Singhal, and S.K. Kailasa, Dithiocarbamate-calixarene functionalized gold nanoparticles as a selective and sensitive colorimetric probe for assay of metsulfuron-methyl herbicide via non-covalent interactions. Sens. Actuators B Chem. **237**, 1044 (2016)
6. A.S. Afify et al., Development of GC-MS/MS method for environmental monitoring of 49 pesticide residues in food commodities in Al-Rass, Al-Qassim region, Saudi Arabia. Arabian J. of Chem. **15**, 104199 (2022)
7. C.Y. Ke et al., Bioremediation of oily sludge by solid complex bacterial agent with a combined two-step process. Ecotoxicol Environ. Saf. **208**, 111673 (2021)
8. H. Zhang, X. Yuan, T. Xiong, H. Wang, and L. Jiang, Bioremediation of co-contaminated soil with heavy metals and pesticides: Influence factors, mechanisms and evaluation methods. Chem. Engineer. J. **398**, (2020)
9. A.A. Zhang, P.P. Sutar, Q. Bian, X.M. Fang, J. B. Ni, and H. W. Xiao, Pesticide residue elimination for fruits and vegetables: the mechanisms, applications, and future trends of thermal and non-thermal technologies. J. of Future Foods **2**, 223 (2022)
10. M. E. Aluffi, C. S. Carranza, N. Benito, K. Magnoli, C.E. Magnoli, and C.L. Barberis, Isolation of culturable mycota from Argentinean soils exposed or not-exposed to pesticides and determination of glyphosate tolerance of fungal species in media supplied with the herbicide. Rev. Argent. Microbiol. **52**, 221 (2020)
11. C. Qu et al., Residues of hexachlorobenzene and chlorinated cyclodiene pesticides in the soils of the Campanian Plain, southern Italy. Environmental Pollution, **231**, pp. 1497 (2017)
12. L. T. Nhi-Cong et al., Advanced materials for immobilization of purple phototrophic bacteria in bioremediation of oil-polluted wastewater. Chemosphere, **278**, p. 130464 (2021)
13. H. C. Lee, H. Chen, M. C. Lin, C. H. Chang, M. J. Chuang, and H. Y. Yin, "A method for ex-post benefit-cost assessment for engineering remediation of debris flow impacts," Eng Geol, **286**, 106084 (2021)
14. S. M. Miles, E. Asiedu, A. lynne Balaberda, and A. C. Ulrich, .Oil sands process affected water sourced Trichoderma harzianum demonstrates capacity for mycoremediation of naphthenic acid fraction compounds. Chemosphere **258**, 127281 (2020)
15. M. A. Sadañoski et al., Mycoremediation of high concentrations of polychlorinated biphenyls with Pleurotus sajor-caju LBM 105 as an effective and cheap treatment. J. Environ. Chem. Eng. **7**, (2019)
16. A. S. Purnomo, A. Sariwati, and I. Kamei, Synergistic interaction of a consortium of the brown-rot fungus Fomitopsis pinicola and the bacterium Ralstonia pickettii for DDT biodegradation. Heliyon, **6**, e04027 (2020)

17. J. Lee, Y. Ko, S. Kim, and H. Hur, Highly effective biosorption capacity of Cladosporium sp. strain F1 to lead phosphate mineral and perovskite solar cell PbI 2, J. Hazard Mater. **442**, 130106 (2023)
18. N. Li et al., Response of extracellular carboxylic and thiol ligands (oxalate, thiol compounds) to Pb2+ stress in Phanerochaete chrysosporium. Environ. Sci. and Pollut. Res. **22**, 12655 (2015)
19. P. Matúš, P. Littera, B. Farkas, and M. Urík, Review on performance of aspergillus and penicillium species in biodegradation of organochlorine and organophosphorus pesticides. Microorganisms **11**, (2023)
20. A. Vaksmaa, S. Guerrero-Cruz, P. Ghosh, E. Zeghal, V. Hernando-Morales, and H. Niemann, Role of fungi in bioremediation of emerging pollutants. Frontiers in Marine Science, **10**. Frontiers Media S.A., (2023)
21. R. Bhadouria, S. Das, A. Kumar, R. Singh, and V. K. Singh, Mycoremediation of agrochemicals. in Agrochemicals Detection, Treatment and Remediation: Pesticides and Chemical Fertilizers, (Elsevier, 2020)
22. K. L. Njoku, P. O. Eludini, A. A. Adesuyi, and E. O. Ude, Physiological and molecular characterization of active fungi in pesticides contaminated soils for degradation of glyphosate (2020)
23. M. S. Wani, Y. R. Tantray, N. A. Malik, M. I. Dar, and T. Ahmad, Microbial bioremediation of pesticides/herbicides in soil. in Microbiota and Biofertilizers, Vol 2: Ecofriendly Tools for Reclamation of Degraded Soil Environs, (Springer International Publishing, 2021)
24. E. Abatenh, B. Gizaw, Z. Tsegaye, and M. Wassie, The role of microorganisms in bioremediation- A Review. Open J. Environ. Biol. **2**, 38 (2017)
25. S. Kumar, G. Kaushik, M. A. Dar, S. Nimesh, U. J. López-Chuken, and J. F. Villarreal-Chiu, Microbial degradation of organophosphate pesticides: A Review. Pedosphere **28**, 190 (2018)
26. S. Mwafulirwa, Isolation characterization and diversity of indigenous pesticide degrading microbes from selected agro ecological zones of Malawi. Asian Plant Res. J. **11,** 29 (2023)
27. S. Gangola, S. Joshi, G. Bhandari, P. Bhatt, S. Kumar, and S. C. Pandey, Omics approaches to pesticide biodegradation for sustainable environment. (Academic Press, 2023)
28. F. Mohamadhasani and M. Rahimi, Growth response and mycoremediation of heavy metals by fungus Pleurotus sp.. Sci. Rep. **12**, (2022)
29. M. Lykogianni, E. Bempelou, F. Karamaouna, and K. A. Aliferis, Do pesticides promote or hinder sustainability in agriculture? The challenge of sustainable use of pesticides in modern agriculture. Sci. of the Total Environ. **795**, 148625 (2021)
30. B. Zhou and X. Li, The monitoring of chemical pesticides pollution on ecological environment by GIS. Environ. Technol. Innov. **23**, 101506 (2021)
31. J. Hu et al., Raman spectrum classification based on transfer learning by a convolutional neural network: Application to pesticide detection. Spectrochim Acta A Mol. Biomol. Spectrosc. **265**, 120366 (2022)
32. S. Kolesnyk, N. Bubalo, M. Prodanchuk, and P. Zhminko, Differences in classification for skin corrosion/irritation in EU and Ukraine: Case study of alternative (in vitro and in silico)methods application for classification of pesticide active ingredient imazamox. Toxicology in Vitro, **60**, 71 (2019)
33. S. Poomagal, R. Sujatha, P. S. Kumar, and D. V. N. Vo, A fuzzy cognitive map approach to predict the hazardous effects of malathion to environment (air, water and soil). Chemosphere, **263**, 127926 (2021)

34. O. A. Salama, M. M. Attia, and M. A. S. Abdelrazek, Modulatory effects of swimming exercise against malathion induced neurotoxicity in male and female rats. Pestic. Biochem. Physiol. **157**, 13 (2019)
35. W. Wang et al., Toxic effects and possible mechanisms following malathion exposure in porcine granulosa cells. Environ. Toxicol. Pharmacol. **64**, 172 (2018)
36. J. Lee, Y. Ko, S. Kim, and H. Hur, Highly effective biosorption capacity of Cladosporium sp. strain F1 to lead phosphate mineral and perovskite solar cell PbI 2. J. Hazard Mater. **442**, 130106 (2023)
37. B. Seth, A. Yadav, S. Agarwal, S. K. Tiwari, and R. K. Chaturvedi, Inhibition of the transforming growth factor-/SMAD cascade mitigates the anti-neurogenic effects of the carbamate pesticide carbofuran. J. of Biolog. Chem. **292**, 19423 (2017)
38. J. Zhang et al., Carbamate pesticides exposure and delayed physical development at the age of seven: Evidence from the SMBCS study. Environ. Int. **160**, 107076 (2022)
39. Z. Qi et al., Effects of prenatal exposure to pyrethroid pesticides on neurodevelopment of 1-year- old children: A birth cohort study in China. Ecotoxicol. Environ. Saf. **234**, 113384 (2022)
40. N. Bravo, M. Garí, and J. O. Grimalt, Occupational and residential exposures to organophosphate and pyrethroid pesticides in a rural setting. Environ. Res. **214**, 1 (2022)
41. W. Bai, G. Qin, J. Wang, L. Li, and Y. Ni, 2-Aminoterephthalic acid co-coordinated Co-MOF fluorescent probe for highly selective detection of the organophosphorus pesticides with p-nitrophenyl group in water systems. Dyes and Pigments **193**, 109473 (2021)
42. D. González-Abradelo et al., First demonstration that ascomycetous halophilic fungi (Aspergillus sydowii and Aspergillus destruens) are useful in xenobiotic mycoremediation under high salinity conditions. Bioresour. Technol. **279**, 287 (2019)
43. J. Chang et al., Bioremediation of Hg-contaminated soil by combining a novel Hg-volatilizing Lecythophora sp. fungus, DC-F1, with biochar: Performance and the response of soil fungal community. Sci. of the Total Environ. **671**, 676 (2019)
44. Y. Xie et al., Characterization of the Cd-resistant fungus Aspergillus aculeatus and its potential for increasing the antioxidant activity and photosynthetic efficiency of rice. Ecotoxicol. Environ. Saf. **171**, 373 (2019)
45. A. Hassan, A. Pariatamby, I. C. Ossai, and F. S. Hamid, Bioaugmentation assisted mycoremediation of heavy metal and/metalloid landfill contaminated soil using consortia of filamentous fungi. Biochem. Eng. J. **157**, 107550 (2020)
46. Y. Wang, X. Ma, M. Saleem, Y. Yang, and Q. Zhang, Effects of corn stalk biochar and pyrolysis temperature on wheat seedlings growth and soil properties stressed by herbicide sulfentrazone. Environ. Technol. Innov. **25**, 102208 (2022)
47. D. Obregon, O. R. Guerrero, E. Stashenko, and K. Poveda, Natural habitat partially mitigates negative pesticide effects on tropical pollinator communities. Glob. Ecol. Conserv. **28**, e01668 (2021)
48. G. Morales-Guzmán *et al.*, Diesel degradation by emulsifying bacteria isolated from soils polluted with weathered petroleum hydrocarbons. Appl. Soil Ecol. **121**, 127 (2017)
49. G. Teran-Cuadrado and E. Polo-Cuadrado, Effectiveness of a bio-catalytic agent used in the bioremediation of crude oil-polluted seawater. Heliyon **7**, (2021)
50. H. S. Saudy, I. M. El-Metwally, and M. G. Shahin, Co-application effect of herbicides and micronutrients on weeds and nutrient uptake in flooded irrigated rice: Does it have a synergistic or an antagonistic effect?. Crop Protect. **149**, 105755 (2021)
51. J. Abraham and A. Gajendiran, Biodegradation of fipronil and its metabolite fipronil sulfone by Streptomyces rochei strain AJAG7 and its use in bioremediation of contaminated soil. Pestic. Biochem, Physiol. **155**, 90 (2019)

52. L. Leino *et al.*, Classification of the glyphosate target enzyme (5-enolpyruvylshikimate-3-phosphate synthase) for assessing sensitivity of organisms to the herbicide. J. Hazard Mater. **408**, 1 (2021)
53. S. Ruuskanen *et al.*, Ecology & evolution ecosystem consequences of herbicides : the role of microbiome. Trends Ecol. Evol. **38**, 1 (2022)
54. C. Li *et al*., Effects of interactions between polygalacturonase and pesticide residues during enzymatic hydrolysis on the yield of apple juice. Lwt **147**, 111562 (2021)
55. A. Gupta, R. F. Landis, and V. M. Rotello, Nanoparticle-Based antimicrobials : Surface functionality is critical. **5**, 1 (2018)
56. A. Sarker, R. Nandi, J. E. Kim, and T. Islam, Remediation of chemical pesticides from contaminated sites through potential microorganisms and their functional enzymes: Prospects and challenges. Environ. Technol. Innov. **23**, 101777 (2021)
57. S. F. Ahmed *et al.*, Heavy metal toxicity, sources, and remediation techniques for contaminated water and soil. Environ. Technol. Innov. **25**, 102114 (2022)
58. P. Kaur and C. Balomajumder, Bioremediation process optimization and effective reclamation of mixed carbamate-contaminated soil by newly isolated Acremonium sp.. Chemosphere **249**, 125982 (2020)
59. A. P. Pinto *et al.*, Degradation of terbuthylazine, difenoconazole and pendimethalin pesticides by selected fungi cultures. Sci. of the Total Environ. **435-436**, 402 (2012)
60. [60] C. L. Barberis, C. S. Carranza, K. Magnoli, N. Benito, and C. E. Magnoli, Development and removal ability of non-toxigenic Aspergillus section Flavi in presence of atrazine, chlorpyrifos and endosulfan. Rev Argent Microbiol, vol. 51, no. 1, pp. 3-11, Jan. 2019, https://doi.org/10.1016/j.ram.2018.03.002
61. G. D. A. Pinto, I. M. Castro, M. A. L. Miguel, and M. G. B. Koblitz, Lactic acid bacteria - Promising technology for organophosphate degradation in food: A pilot study. LWT **110**, 353 (2019)
62. A. Abdel-Fattah Mostafa, M. T. Yassin, T. M. Dawoud, F. O. Al-Otibi, and S. R. Sayed, Mycodegradation of diazinon pesticide utilizing fungal strains isolated from polluted soil. Environ. Res. **212**, 113421 (2022)
63. J. Sivakumar, Rejuvenation of pesticide polluted soil from the isolated microbial flora of agricultural field. Asian J. of Sci. and Appl. Tech. **12**, 25 (2023)
64. A. S. Purnomo, A. Sariwati, and I. Kamei, Synergistic interaction of a consortium of the brown-rot fungus Fomitopsis pinicola and the bacterium Ralstonia pickettii for DDT biodegradation. Heliyon **6**, e04027 (2020)
65. O. Akhtar, H. K. Kehri, and I. Zoomi, Arbuscular mycorrhiza and Aspergillus terreus inoculation along with compost amendment enhance the phytoremediation of Cr-rich technosol by Solanum lycopersicum under field conditions. Ecotoxicol. Environ. Saf. **201**, 110869 (2020)
66. P. Kaur and C. Balomajumder, Bioremediation process optimization and effective reclamation of mixed carbamate-contaminated soil by newly isolated Acremonium sp.. Chemosphere **249**, 125982 (2020)
67. P. Kaur and C. Balomajumder, Effective mycoremediation coupled with bioaugmentation studies: An advanced study on newly isolated Aspergillus sp. in Type-II pyrethroid-contaminated soil. Environ. Pollut. **261**, 114073 (2020)
68. C. L. Barberis, C. S. Carranza, K. Magnoli, N. Benito, and C. E. Magnoli, Development and removal ability of non-toxigenic Aspergillus section Flavi in presence of atrazine, chlorpyrifos and endosulfan. Rev. Argent. Microbiol. **51**, 3 (2019)
69. P. R. S. Soares, W. G. Birolli, I. M. Ferreira, and A. L. M. Porto, Biodegradation pathway of the organophosphate pesticides chlorpyrifos, methyl parathion and profenofos by the marine-derived fungus Aspergillus sydowii CBMAI 935 and its potential for methylation reactions of phenolic compounds. Mar. Pollut. Bull. **166**, (2021)

70. M. Govarthanan et al., Rapid biodegradation of chlorpyrifos by plant growth-promoting psychrophilic Shewanella sp. BT05: An eco-friendly approach to clean up pesticide-contaminated environment. Chemosphere **247**, 125948 (2020)
71. A. P. Pinto et al., Degradation of terbuthylazine, difenoconazole and pendimethalin pesticides by selected fungi cultures. Sci. of the Total Environ. **435-436**, 402 (2012)
72. M. A. Zhao, H. Gu, C. J. Zhang, I. H. Jeong, J. H. Kim, and Y. Z. Zhu, Metabolism of insecticide diazinon byCunninghamella elegansATCC36112. RSC Adv. **10**, 19659 (2020)
73. S. O. Egbewale, A. Kumar, M. P. Mokoena, and A. O. Olaniran, Metabolic biodegradation pathway of fluoranthene by indigenous Trichoderma lixii and Talaromyces pinophilus spp.. Catalysts. **13**, (2023)
74. A. P. Pinto, D. M. Teixeira, A. T. Caldeira, and S. C. Rodrigues, Biodegradation of pesticides by adapted fungi. Potential use on biopurification systems?. in Agrochemicals Detection, Treatment and Remediation: Pesticides and Chemical Fertilizers, (Elsevier, 2020)
75. N. Khan et al., Mycelial nutrient transfer promotes bacterial co-metabolic organochlorine pesticide 1 degradation in nutrient-deprived environments 2 3 4,
76. S. Rana, P. Mardarveran, R. Gupta, L. Singh, and Z. ab Wahid, Role of Microbes in Degradation of Chemical Pesticides. in Microbes and Enzymes in Soil Health and Bioremediation, A. Kumar and S. Sharma, Eds., (Singapore: Springer Singapore, 2019)
77. F. E. 1 Adelowo, O. A. 2 Olu-Arotiowa, and O. S. 1 Amuda, Advances in Bioscience and Bioengineering Biodegradation of Glyphosate by Fungi Species. **2**, 104 (2014)
78. S. Anode and J. Onguso, Current Methods of Enhancing Bacterial Bioremediation of Pesticide Residues in Agricultural Farmlands. in Microbial Rejuvenation of Polluted Environment: Volume 2, D. G. Panpatte and Y. K. Jhala, Eds., (Singapore: Springer Singapore, 2021)
79. N. Khan et al., Mycelial nutrient transfer promotes bacterial co-metabolic organochlorine pesticide degradation in nutrient-deprived environments. ISME J. **17**, 570 (2023)
80. R. Kataoka, Biodegradability and biodegradation pathways of chlorinated cyclodiene insecticides by soil fungi. J. Pestic. Sci. **43**, 314 (2018)
81. T. Wang, Mechanism study of cyfluthrin biodegradation by Photobacterium ganghwense with comparative metabolomics. Appl. Microbiol. Biotechnol. **103**, 473 (2019)
82. E. R. Rene, E. Sahinkaya, A. Lewis, and P. N. L. Lens, Sustainable heavy metal remediation Volume 2: Cas. studi. **8**, (2017)
83. P. Anusha et al., Assessment of hexavalent chromium (VI) biosorption competence of indigenous Aspergillus tubingensis AF3 isolated from bauxite mine tailing. Chemosphere **282**, 131055 (2021)
84. A. Kumar, S. Arora, K. K. Jain, and K. K. Sharma, Metabolic coupling in the co-cultured fungal-yeast suite of Trametes ljubarskyi and Rhodotorula mucilaginosa leads to hypersecretion of laccase isozymes. Fungal. Biol. **123**, 913 (2019)
85. Y. H. Lee, N. K. Verma, and T. Thanabalu, Prebiotics in atopic dermatitis prevention and management. J. Funct. Foods **78**, 104352 (2021)
86. D. Tian et al., A new insight into lead (II) tolerance of environmental fungi based on a study of Aspergillus niger and Penicillium oxalicum. Environ. Microbiol. **21**, 471 (2019)
87. J. Wang, Biotransformation and detoxification of the neonicotinoid insecticides nitenpyram and dinotefuran by Phanerochaete sordida YK-624. Environ. Pollut. **252**, 856 (2019)
88. B. V. Mohite, S. H. Koli, C. P. Narkhede, S. N. Patil, and S. V. Patil, Prospective of Microbial Exopolysaccharide for Heavy Metal Exclusion. Appl. Biochem. Biotechnol. **183**, 582 (2017)

89. O. A. Salama, M. M. Attia, and M. A. S. Abdelrazek, Modulatory effects of swimming exercise against malathion induced neurotoxicity in male and female rats. Pestic. Biochem. Physiol. **157**, 13 (2019)
90. S. Jain et al., Exogenous addition of silicon alleviates metsulfuron methyl induced stress in wheat seedlings. Plant Physiol. and Biochem. **167**, 705 (2021)
91. A. Hassan, A. Pariatamby, I. C. Ossai, and F. S. Hamid, Bioaugmentation assisted mycoremediation of heavy metal and/metalloid landfill contaminated soil using consortia of filamentous fungi. Biochem. Eng. J. **157**, 107550 (2020)
92. M. A. Ram, Route of Exposure and Impact of Pesticides Pollution on Human Health and Aquatic Ecosystem. Int. J. of Zoolog. Investig. **08**, 85 (2022)
93. S. Keshavarz, F. Faraji, F. Rashchi, and M. Mokmeli, Bioleaching of manganese from a low-grade pyrolusite ore using Aspergillus niger: Process optimization and kinetic studies. J. Environ. Manag. **285**, 112153 (2021)
94. P. Tripathi et al., Bioremediation of arsenic by soil methylating fungi: Role of Humicola sp. strain 2WS1 in amelioration of arsenic phytotoxicity in Bacopa monnieri L. Sci. of the Total Environ. **716**, 136758 (2020)
95. L. Hou, L. Zhang, X. Chen, X. Li, ZengqiangZhang, and Y. B. Lin, The benefits of biochar: Enhanced cadmium remediation, inhibited precursor production of nitrous oxide and a short-term disturbance on rhizosphere microbial community. Environ. Pollut. **272**, 116040 (2021)
96. D. Damodaran, K. Vidya Shetty, and B. Raj Mohan, Uptake of certain heavy metals from contaminated soil by mushroom-Galerina vittiformis. Ecotoxicol. Environ. Saf. **104**, 414 (2014)
97. D. Damodaran, K. Vidya Shetty, and B. Raj Mohan, Effect of chelaters on bioaccumulation of Cd (II), Cu (II), Cr (VI), Pb (II) and Zn (II) in Galerina vittiformis from soil. Int. Biodeterior Biodegradation **85**, 182 (2013)
98. D. Mani and C. Kumar, Biotechnological advances in bioremediation of heavy metals contaminated ecosystems: An overview with special reference to phytoremediation. Int. J. of Environ. Sci. and Tech. **11**, 843 (2014)
99. P. Dey, Mechanistic insight to mycoremediation potential of a metal resistant fungal strain for removal of hazardous metals from multimetal pesticide matrix. Environ. Pollut. **262**, (2020)
100. O. O. Kuforiji and I. O. Fasidi, Enzyme activities of Pleurotus tuber-regium (Fries) Singer, cultivated on selected agricultural wastes. Bioresour. Technol. **99**, 4275 (2008)