MINI REVIEW

Mycoremediation: A Step towards Sustainability

Manisha Mishra, Deepa Srivastava*

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Abstract

Mycoremediation is a new wave of cutting-edge technology in this era that incorporates fungi in nursing environment damaged by toxins. Instigating fungi to such contaminated places leads the way for the natural cleaning process. Waste treatment plants running on incinerators, exercising physical and chemical methods, are injurious to the health of organisms and the environment. They lead to life-threatening diseases and negative soil pollution. Eco-friendly and secure techniques are to be employed for their management. Microfungi, as well as macrofungi, help in this procedure. They degrade environmental wastes as heavy metals, aromatic hydrocarbons, polychlorinated compounds, organic compounds by their extracellular enzymes without harming any natural component of soil. Demand and the need for reaching net-zero emission remain farsighted deed in the current scenario of rapid industrialization. Therefore, merging of the fungi with new techniques can speed up other processes of sustainable recovery of hazardous pollutants that may help in fighting against deleterious pollution levels. Their enzymes assert a great role and help in xenobiotic degradation rendering land and water clean and safe. Nevertheless, they do not have any special growth demand. White rot fungi and many mushrooms can grow on a wide range of substrates. The most common being sawdust, agricultural waste, and straw. Their biosorption efficiency helps to reclaim contaminated land. Ligninolytic enzymes uphold the mycoremediation process. In this review, we have encapsulated the mycoremediation of toxic substances by various genera and species of fungi along with the mechanisms involved. The aim is to precisely draw attention to the magnificently inherited traits of fungi that make them apt for the remediation process.

Keywords: Heavy metals, Lignin, Mycoremediation, Polycyclic aromatic hydrocarbons, White rot fungi.

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Introduction

With the advent of the 21st century, there has been a raging soar for undertaking steps to balance climate change ranging from mitigating cumulative carbon dioxide emissions to meeting safe waste disposition and management works. An inadequate chemical and physical procedure to meet these demands in a holistic approach has laid us back to readdress a biological method for the degradation process. Solid or liquid waste discarded on open land areas or water bodies remains for years without any treatment hindering human and livestock activities. This leads to a reduction in landmass, a major challenge in developing cities. The arrival of such wastes into the food chain leads to bioaccumulation together with biomagnification, jeopardizing the whole biotic community. Furthermore, loosing of unimpeded chemicals from industries and raw products as heavy metals, toxic chemical salts, xenobiotics, dyes, petroleum products, pesticides, and e-waste has led us to embrace a thoroughgoing process that works by replenishing compounds which can be advantageous to the ecosystem.

Currently, preferable methods are bioremediation, bioaugmentation, and rhizoremediation that not only involve living organisms to curb environmental pollution but also have an efficiency in the decontaminating process are gaining popularity. Micro-organisms involved here help to transform the complex hydrocarbons. To reach the control goals of reducing carbon dioxide pollution, carbon accumulation through vegetable biomass can be an effective remedy, and fungi may serve a key part. The role of fungi over toxic remediation is seeking attention nowadays. They are the hidden warriors covering acres of forest land and remaining much invisible hence helping in regulating atmospheric carbon dioxide levels.

Mycoremediation demands the utilization of fungal biomass to further fragment complex environmental and hazardous industrial pollutants. Fungal mycelium facilitates carbon sequestration, biodiversity preservation; their hyphae bind well with the soil, thus allowing the soil to retain water through water percolation. The Meta-proteomics method incorporates evaluating complete protein aggregates in any habitat at a given rate. It scans absolute protein content among microbial communities dwelling in certain environments. (Hart *et al*., 2018). Estimation of 16S rRNA genes in contaminated habitats provided details on microorganisms colonizing natural surroundings. The behaviour of mRNA genes in mycoremediation permits flexibility about the metabolic entities of microorganisms in polluted areas (Lovely, 2003). Such genomic tools are gaining popularity nowadays in evaluating genotypes of microbes (Han *et al*., 2020).

Department of Botany, Deen Dayal Upadhyay Gorakhpur University, Gorakhpur-273009, Uttar Pradesh, India

***Corresponding author:** Dr. Deepa Srivastava, Department of Botany, Deen Dayal Upadhyay Gorakhpur University, Gorakhpur-273009, Uttar Pradesh, India, Mobile: +91-9984468918; Email: drdeepasrivastav@gmail.com

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Bioremediation using Fungi

Bioremediation is a process that engages living organisms, mainly bacteria, and microbes to decontaminate polluted communities. Anthropogenic practices have had an impact on the well-being of the ecosystem in the form of negative environmental repercussions as pollution. Mycoremediation, a term coined by Stamets (2005), enumerates the process of utilizing fungi to attain a lesser polluted environment. On account of the capabilities inherited by fungi to degrade cellulose and lignin, breakdown of toxic chemicals, they are named as natural decomposers assisting soil formation. Mycoremediation can happen at three primary places in a fungal cell that is on the surface, extracellular environment, or intracellular environment. They are dominating biomass of soil but not much exploited for bioremediation (Singh *et al*., 2015). Filamentous fungus species also have their bit part in degrading waste owing to their mycelial ability to acclimatize to extreme climate conditions. Filamentous fungi producing mycotoxins also have a role in solid waste management. Recent studies are being conducted to elucidate the role of filamentous fungi for the bioremediation process that can be bioseparation of suspended solids (Barrech *et al*., 2018).

Besides distinct pharmaceutical and nutraceutical qualities, fungi can also absorb carbon and help in cleaning polluted soils. Stamets (2005) discussed an experiment that demonstrated *Pleurotus ostreatus* to be effective in remediating oil spills. Mycelium spores were spread on a given area, and growth of oyster mushroom was noted down that subsequently became a spot of insects and bird attraction, being primary facets of ecosystem foundation. Mycoremediation is a site-specific phenomenon. It involves cleaning hazardous waste through fungi by harnessing their inherent ability of enzymatic breakdown (Table 1). Plastics are non-biodegradable polymers that last in the environment. Their remediation by fungi is also reported by *Pleurotus ostreatus* (Luz *et al*., 2013). Merits of Mushroom in bioremediation owe to its high accumulation rate of heavy metals like lead, cadmium, magnesium, nickel since mushrooms require these elements for their metabolic processes (Gast *et al*., 1988).

Mushrooms renew polluted soil via 3 steps biodegradation, bioconversion, and biosorption. Extracellular enzyme production (peroxidases, cellulases, ligninase) aids polycyclic aromatic hydrocarbons (PAHs) degradation (Nyanhongo *et al*., 2007). A bioconversion end product, mushroom, can be cultivated on lignin and cellulose waste. They can bio-transform the vegetable biomass into carbohydrates (beta-glucan), proteins, enzymes (Khaund and Joshi, 2014; Kozarski *et al*., 2015).

Biosorption is the assimilation of heavy metals from an aqueous solution by utilizing energy. This process aids heavy metal remediation. Fungal mass carrying out this process binds heavy metals on their surface. *Pleurotus tuber-regium* can bio-absorb heavy metals from soil polluted with fertilizers (Adongbede and Okhuoya, 2011). *Volvariella volvacea*, *Tricholoma saponaceum*, and *Pleurotus sajor-caju* efficiently uptake heavy metals, but the metals had a toxic effect on the species (Purkayastha and Mitra, 1992; Kim and Kim, 2001; Jain *et al*., 1988). Toxicity may be attributed to the low enzymatic breakdown of compounds, which may be lethal for the mushrooms. Such mushrooms are regarded as hazardous wastes, so they become unfit for consumption. As mycelial growth occurs on agricultural waste, the whole process being biological is not expensive or habitat destructive. *Aspergillus tubingensis* can grow on plastic surfaces and help in the bioremediation of polymer.

Clemmensen *et al*. (2013) reported the fact that around 70 percent of the carbon treasured inside boreal forests comes from dead roots and associated fungi (mycorrhizal association). *Cryptococcus neoformans* can withstand irradiation. Their melanized form was isolated from the Chernobyl nuclear power plant with highly irradiated surroundings. Melanin scavenges

Table 1: An overview of a few toxic compounds and the fungi involved in their remediation

S.No.	*Name of Fungi*	*Compounds*	*References*
1.		Heavy metals	
	Agaricus bisporus, *Lactarius piperatus*, *Pleurotus ostreatus*	Cadmium	Tay *et al*. (2011); Nagy *et al.* (2013)
	Flammulina velutipes	Copper	Luo *et al*. (2013)
2.	*Trametes hirsute*		Abadulla *et al*. (2000)
	Aspergillus flavus	Textile dyes	Andleeb *et al*. (2012)
	Aspergillus niger, Trichoderma viride		Jebapriya and Gnanadoss (2013)
3.	*Exophiala xenobiotica, Aspergillus flavus*	Petroleum products	Adekunle and Oluyode (2005); Isola *et al*. (2013)
		PAHs	
	Pleurotus ostreatus	i. Diphenyl ether	Rosales *et al*. (2013)
4.	*Armillaria* sp.	ii. Anthracene	Hadibarata *et al*. (2013)
	Aspergillus niger	iii. Benzopyrene	Wunder *et al*. (1994)
	Aspergillus niger, Agrocybe aegerita	iv. Pyrene	Hammel *et al*. (1986)
5.		Pesticides	
	Trametes pubescens	i. Chlorophenols	Denizli *et al*. (2005)
	Mucor alternans	ii. DDT	Anderson and Lichtenstein (1971)
	Fusarium oxysporum	iii. DDT	Engst and Kujawa (1968)
	White Rot Fungi	iv. Chlorinated pollutants	Arisoy (1998)

free radicals and, thus, it is reported to have shielding attributes in a highly irradiated environment (Dadachova and Casadevall, 2008).

Unique enzyme chain allows the fungi to digest lignocellulose, furnishing them with a crucial function inside to balance the carbon circle. The hydrocarbon chains, once broken, their nutrients are locked up in cellulose are ready to be used by plants. Toxic substances are broken down into less or nontoxic forms. Despite the enormous potential that mycoremediation holds, it has not been commercialized for large-scale usage. Fungi thriving in extreme climates are very economical for industrial purposes due to their tolerance of harsh conditions.

Their merits over bacteria correspond to the ubiquitous presence, greater growth proportion, hyphae network, production of degrading enzymes, and metal accumulation potential.

Mycoremediation of Heavy Metals

A definite group of heavy metals like Ag (Silver), Hg (Mercury), Mn (Manganese), Cu (Copper), Ni (Nickel), Sb (Antimony) constitute the Earth's crust, having high densities and atomic weights. They gain access to the food chain through polluted water, soil, food, and air sources. Usage of fertilizers and pesticides leads them to get incorporated into food products that we consume. A high concentration of heavy metals may actually have poisoning effects as they tend to bioaccumulate. They break into the water supply through industrial discharge that is being discarded in water-bodies and, in turn, altering human health by giving rise to liver and kidney damage, cancer, bone defects, gastrointestinal problems, and neurological disturbances.

Cadmium is present in phosphate fertilizers, alloys, PVCs (Polyvinyl Chloride), and petroleum products. Lead, mercury is present in batteries, cables and is emitted from coal combustion. Intake of contaminated water led to chronic diseases, for instance, Minamata disease in Japan that was caused due to consumption of methylmercury contaminated fishes (Harada, 1995). Under excavating projects, cadmium was released into water-bodies, and rice cultivated using such contaminated water led to biomagnification in the human population. Consequently, Itai-Itai disease affected the people in that area (Abernethy *et al.*, 2010). Living fungi could be utilized to withdraw heavy metals appropriately from an aqueous medium as well as industrial effluents (Srivastava and Thakur, 2006).

Many other lethal diseases are due to heavy metal poisoning. Fungi have helped in eliminating heavy metals by displacing them from the soil and assembling them in their mycelia and fruiting bodies for further breakdown. Re-establishment of contaminated areas is executed employing macrofungi. A few macrofungal species incorporated in mycoremediation of heavy metals are *Pleurotus ostreatus*, *Calocybe indica*, *Agaricus bisporus*, *Boletus edulis*, and *Polyporus* sp. (Urban *et al.*, 2005).

Microfungi, *Aspergillus niger*, has manifested to be a superior entity for chromium (Cr) remediation as it can stand and store up heavy metals (Thippeswamy *et al.*, 2012). Maximum accumulation was of Pb (75.81%) accompanied by Zn (49.39%), Cu (45.35%), and Ni (25.20%). Biosorption of heavy metals has been seen in *Aspergillus flavus* with 22% Pb and 20% Cu aggregation (Akar and Tunali, 2006). Divergent strains of *Trichoderma*, *Penicillium*, and *Fusarium* can reduce and methylate arsenic as observed by X-Ray absorption studies (Su *et al.*, 2012). Arsenic (As), a toxic pollutant and carcinogen, turns water non-potable and unfit for irrigation gradually sets foot in people consuming it. M. Singh *et al.* (2015) isolated 54 fungal strains from the middle Indo-Gangetic Plains. Often encountered species were of *Aspergillus*, *Trichoderma*, *Rhizopus*, as well as *Chaetomium* species - making these candidates of arsenic mycoremediation. Arsenic uptake is believed to occur through glycerol, phosphate, and hexose transporters (Tsai *et al.*, 2009).

The paper and pulp industry are among the pioneers of heavy metal impurities having Cu, Cd, Mg, Mn in the highest concentration. *Aspergillus* and *Mucor* species have been reported to pile them up in higher amounts. *Mucor* species prospers under abiotic stress conditions. *Mucor circinelloides* help *in-situ* bioremediation, and their activity can be enhanced by lessening ATPase activity (Zhang *et al.*, 2017). Fungi have been elucidated to be least affected among a group of microbes in a study on culturable soil microbial population and the effect of antimony and arsenic on them (Wang *et al.*, 2011). The outcome of five heavy metals (Copper, Zinc, Lead, Mercury, and Cadmium) on the growth of *Pleurotus tuber-regium*. Bioaccumulation of zinc was the highest (183.06 mg/kg at 2 m mol/L). Cd accumulation was satisfactory in contrast to Hg, which averted the growth. Pb affected the stipe morphology (Akpaja *et al.*, 2012). He *et al.* (2018) reported that the species abundance kept reducing on incrementing uranium concentration. It led to the stimulation of certain functional genes, which can be integrated to gain in-depth knowledge of ecosystem parameters.

Mycoremediation using White-Rot Fungi

The unequalled potential of the white-rot fungi (WRF) in decaying lignin (heterogenous polyphenolic polymer) relates to them exhibiting enzymes that are lignin modifying. Thus, can eliminate environmental pollutants explicitly, herbicides, polychlorinated biphenyls (PCBs), organochlorines, and pesticides. The result of lignin degradation is a white-coloured appearance of wood and hence the name. These belong mostly to basidiomycetes and quite a few to ascomycetes. Being natural decomposers, they require a substrate for growth on pollutants such as polycyclic aromatic hydrocarbons, especially in soil. Their enzymes help in providing substrate for growth (Reddy, 1995; Baldrian *et al.*, 2000; Pointing, 2001). Ligninolytic enzymes help in bio-transforming organic pollutants (Rodriguez-Rodriguez *et al.*, 2013).

Comprising a few white-rot fungi are *Fomes fomentarius*, *Ganoderma lucidum*, *Pleurotus ostreatus*, *Trametes* sp., *Lentinula edodes*, *Trichoderma viride*, *Phellinus pini*, and *Rhizopus* sp. *Pleurotus pulmonarius* happens to be tested for crude oil, petroleum, and palm kernel mycoremediation. WRF embraces various mechanisms by integrating their enzymatic gift to degrade petroleum products (Fig. 1). The nutrient value was observed to have increased along with the bioaccumulation of heavy metals (Adenipekun and Lawal, 2011). Syringol derivatives of azo dyes and their decay by *Trametes versicolor* have been trialed by Martin *et al.* (2003). Biodegradation assays have also been executed to measure their possibility of wastewater treatment. Kapdan *et al.* (2000) considered *Coriolus versicolor*

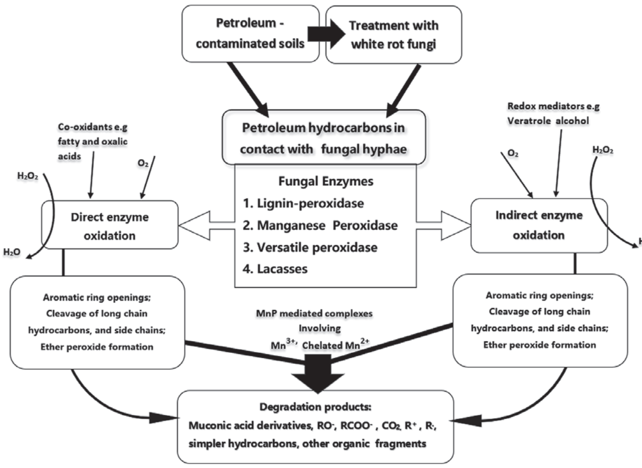

Fig. 1: Mechanism employed in mycoremediation of petroleum-contaminated soil (Adapted from Dickson *et al*., 2019).

to be able of biological decolorization of a textile dye, everzol turquoise blue. *Trametestrogii*, isolated from Tunisia, is also beneficial in the degradation of commercial dyes (Mechichi *et al*., 2006). *Pleurotus ostreatus* and *Irpexlacteus* can generate a range of transformation products (chlorobenzoates, hydroxylated PCBs) by degrading PCB, a soil contaminant. *Pleurotus ostreatus* colonized the respective area and was superior in total to other genera (Stella *et al*., 2017). *Irpex lacteus* seems likely to be an alternative to chemicals for dye decolorization. The fungus produced lignin phosphate (LiP) and laccase enzymes on the medium spread with a heavy amount of nitrogen. It not only grew swiftly but also resisted suppression by soil bacteria - henceforth proving to be an ideal fungus in mycoremediation (Novotný *et al*., 2000). *Lentinus subnudus*, in Nigeria, has been studied to remediate crude oil spills (Adenipekum and Fasidi, 2005).

Enzymes used by WRF in Bioremediation

Lignin, being the principal fungal enzyme aiding the mycoremediation process, is researched extensively by scientists. The fragmented lignin leads to a plentitude of degradation products that are absorbed along by hyphae for being additionally metabolized past the intracellular fungal mesh. Extracellular enzymes assisting lignin degradation by *Phanerochaete chrysosporium* are lignin peroxidase and glyoxal oxidase. Glyoxal oxidase apparently helps to activate lignin peroxidase by oxidizing the metabolites with the reduction of oxygen to water. Lignin peroxidase, in turn, oxidizes non-phenolic aromatic nuclei in lignin (Kirk *et al*., 1992).

Ligninolytic Fungal Enzymes

Usefulness of WRF refers to their enzymes. Lignin peroxidase (a glycated heme protein) stimulates oxidation of unsaturated compounds with planar rings that are related to lignin in a hydrogen peroxide dependent manner. Therefore, with high redox potential, a plethora of chemicals and non-phenolic aromatic compounds can be oxidized (Reddy and Matthew, 2001). The recalcitrant attribute of the lignin enzyme makes it hard to degrade. Conversion of manganese (+2) to manganese (+3) state via oxidation by manganese peroxidase depends on the hydrogen peroxidase method. Oxidation of phenolic substrates is accentuated by the Mn (III) state of the enzyme (Mester and Tien, 2000).

Laccase is the primary enzyme in the degradation process. They are multicopper oxidase enzymes (Viswanath *et al*., 2014) and can operate even in the absence of hydrogen peroxide (Hataka *et al*., 2001). Laccase likely oxidizes numerous aromatic and non-aromatic compounds, but they have a low shelf-life. They tend to engage in oligomerization and polymerization reactions of aromatic compounds. Laccase, combined with ultrasound, increases dye removal precision in wastewater. Nanobiotechnological studies on laccases for biosensor cell implantation have been done (Goncalves *et al*., 2015).

Additional enzymes that are engaged in the mycoremediation process fall under the cellulolytic enzyme category comprising cellulases (*Trichoderma* species), hemicellulases, pectinases, chitinases (*Fusarium* species), amylases (*Aspergillus niger*, *Penicillium* species), and proteases. WRF uses agricultural left over as a substratum for yielding the above-mentioned enzymes. *Trametes versicolor* degrades tribromophenol (TBP) by implying enzyme laccase (Donoso *et al*., 2008). Copper mineralizes lignin (Kües, 2015) and is used to remove water contamination.

Sophisticated and adequately coordinated collaboration between the termites and the fungi allows utilization of lignocellulose. *Termitomyces albuminosus* (a symbiotic fungus) produces extracellular phenol oxidases. Two genes encoding MnP (tam 1 and tam 2) were studied. They have an essential amino acid for peroxidase activity and manganese (Mn II) binding sites, indicating MnP encoding. The symbiotic link between termites and a fungus assists in lignin decomposition and total bio recycling of plant litter (Ohkuma *et al*., 2001). Catalase and polyphenol oxidase could be used to monitor the bioremediation process as their concentration decreases in contaminated soil with oil concentration. The soil was contaminated with different concentrations of oil (Lin *et al*., 2009).

Non-ligninolytic Fungal Enzymes

Besides hydrolytic enzymes, fungi also make use of cyt P450-dependent monooxygenases in addition to glutathione S-transferases enzyme to handle pollutant degradation. Sutherland *et al*. (1995) stated that the metabolism of PAHs occurs by oxidation of aromatic ring to obtain arene oxide. Dioxygenase enzymes are also reported. Apart from this, two fungal cyt P450 monooxygenases, procured out-of *Fusarium oxysporum*, were replicated. Both of them were recognized as wonderful catalysts in the production of ω-hydroxyl fatty acids (Durairaj *et al*., 2015).

Mycoremediation of Polycyclic Aromatic Hydrocarbons (PAHs)

Organic pollutants mostly comprise PAHs, and these are hydrocarbons of a heterogenous group along with multiple aromatic rings. It is generated from the partial decomposition of organic matter emerging through petroleum spills, incinerators, and incomplete combustion of coal, wood (Kadri *et al*., 2017).

Valentin *et al*. (2007) conducted an experiment that projected the ability of *Bjerkandera* fungus species to promote decay of harmful compounds as pyrene, dibenzothiophene, phenalene in a slurry reactor. *Pleurotus ostreatus* helps in PAH removal (Eggen and Majcherzykb, 1998). *Coprinus comatus* basidiocarp harvested from useless paper that had 47.9 ppm lead contamination - finally reported 16.2 ppm lead uptake from the paper pulp (Dulay *et al*., 2012).

The removal efficiency of petroleum hydrocarbon by *Pleurotus tuber-regium* was 20%, 18.7% and 18.8% at contamination rates of 1.0%, 2.5%, and 5.0% respectively. Meanwhile, at the same contamination levels, amid three months, the removal efficiency increased to be around 40%, 39%, and 38%, respectively (in *Pleurotus tuber-regium*), and it was the highest. However, the minimum remediation capacity was observed in *Pleurotus pulmonarius*. The heavy metal and hydrocarbon compound eradication effect of *Pleurotus tuber-regium* was much better than of *Pleurotus ostreatus* and *Pleurotus pulmonarius* (Adewole *et al*., 2017). Pharmaceutical compounds (PhC) persist in water bodies and lead to water toxicity. Wastewater treatment plants are not efficient in their removal (Teijon *et al*., 2010). Demand for fungi-based biological treatment for getting rid of PhC has received recognition due to the work of researchers on this (Gunde-Cimermon *et al*., 2000). PhC as naproxen, codeine, diazepam, metoprolol is also degraded by WRF, *Trametes versicolor* (Asif *et al*., 2017). Purchase *et al*. (2009) communicated about *Beauveria bassiana* isolates from raised marshlands collecting municipality influx, stocked up to 0.6% of zinc and 8.5% of lead. X-Ray spectrophotometric studies outlined that immobilization combined with precipitation might get utilized via strains of fungi to decipher heavy metal uptake, accompanying the biosorption process. *Ganoderma lucidum* is effective in PAH remediation.

16S rRNA phylogeny has been embraced for explaining the conformational dynamics of microbes and their genes linked to the remediation of polycyclic aromatic hydrocarbons. Weighing obtained data with 16S rRNA profiles can give details on intricate taxonomic studies to start a relation between them and proteins (Sakshi and Haritash, 2020). Lignin degrading enzymes as manganese peroxidase and laccases were produced. *Ganoderma lucidum* degraded 99.55% and 99.58% of phenanthrene and pyrene, respectively (Agrawal *et al*., 2018). *Pycnoporus sanguineus* strain degrades 68.0% of anthracene at *in-vivo* conditions and revealed maximum laccase activity. Piperonyl butoxide addition into a liquid culture increased the degradation of anthracene to 73.0%. Zhang *et al*. (2015) also worked to deduce PAHs metabolism by laccases, cyt P450, and laccases present in mycelium.

The pioneering work narrating engagement of *Trichoderma asperellum* H15 strains for polycyclic aromatic compounds degradation in soil was established. The degradation of phenanthrene in heavily contaminated soil was noticed to be approximately 79.9% following two weeks (Zafra *et al*., 2015). Two types of aromatic hydrocarbons, anthracene, and benzathine are reported to be mycoremediated by fungal species confined in polluted coastal saline deposits. GC/MS studies revealed that *Fusarium solani* strains degrade them to give rise to ortho-phthalic acid. Unbound laccase has been diagnosed with extracellularly (Wu *et al*., 2010). *Pleurotus ostreatus* (OST-1) manifested good results in eliminating organochlorines as DDT, HCH, Aldrin, Dieldrin (Sadiq *et al*., 2015). *Trichoderma viride* had been described to remove cyclodienes as aldrin and dieldrin (Kamei *et al*., 2010). Limitation in their removal is due to their hydrophobic nature (Urrea *et al*., 2010). Two saprophytic strains of microfungi, *Trichoderma hamatum*, and *Rhizopus arrhizus* have DDT tolerance and show better results. They demonstrated high metabolic activity for the depletion of carbon sources amidst the attendance of an organochlorine (DDT) in soil. Possession of antioxidant enzymes to level up with the chemical stress-induced by DDT presence (Russo *et al*., 2019).

Mycoremediation by Marine Fungi

Marine fungi thrive under diverse climatic situations (high pH, salinity) and cope up with a harsh atmosphere that prepares them to be resilient. They devour dead organic matter and balance the nutrient recycling, thus, supporting fisheries and providing nutrients to mangroves simultaneously. Chromium toleration, along with their removal potential, has been displayed by *Aspergillus flavus* and *Aspergillus niger*, seaweed-linked fungus species. Their hexavalent chromium resistance has been evaluated, though it increased with increasing Cr (VI) concentration (Vala *et al*., 2004).

Marine fungal strains of *Dendryphiella salina* can absorb approximately 90% of Hg (II) from liquid media. Mendozoa *et al*. (2010) elucidated that Den 32 strains had elevated absorption efficiency as compared to Den 35 strains for Hg bioremediation. Fungi growing in marine habitats, such as *Aspergillus* species and *Rhizopus* species, have been revealed to be arsenic tolerant by accumulating it. They were subjected to 0.025 kg/m^3 and 0.05 kg/m^3 of sodium arsenite. *Rhizopus* is suitable for arsenic remediation in water as deposition increases with the increasing concentration of arsenic (Vala and Sutariya, 2012).

Corollospora lacera along with *Monodictys pelagica* heap up lead, cadmium extracellularly (Taboski *et al*., 2005). Mycoremediation of hexavalent chromium (Cr) by marine fungi, *Trichoderma viride*, in the Mediterranean Sea has been observed. The transmission electron microscopic method revealed that chromium did not hinder its mycelial or conidial structures (El-Kassas and El-Taher, 2009). In a particular study, it has been established about *Aspergillus sydowii* in addition to *Aspergillus destruens* that they facilitate polycyclic aromatic hydrocarbon and chlorinated hydrocarbon elimination in a halophytic environment. Incorporating benzo[a]pyrene with phenanthrene in the form of substrate, they removed these toxins via bioabsorption (González-Abradelo *et al*., 2019). *Aspergillus oryzae* has the potential to eliminate monocyclic aromatic hydrocarbons compounds (Benzene, toluene, hexyl benzene, and xylene) in waste discharge (El-Kassas and El-Taher, 2010).

Conclusion and Future Prospective

Mycoremediation is a sustainable method for cleaning contaminated sites and detoxification of toxic compounds. It is a necessity to make reforms in the scientific and technical arena for a better understanding of various phenomenons. But in the long run of chasing such aims, we should not forget that we have to refrain from creating new problems for our planet. Engaging a lot of heavy machines for degradation of hazardous wastes consumes a lot of power and energy, hence in turn, disrupting surrounding environment. Except for being highly expensive, they also lead to environmental imbalance. The persistence of organic pollutants and heavy metal wastes require strategies directed towards their removal.

By unravelling metabolomics, metagenomics, and meta-transcriptomics, comparative studies on the behaviour and remediation capabilities of discrete fungal colonies in the contaminated area, can be attained. It can also examine new fungal species aiding degradation, their molecular mechanism involved and the methods used to increase the enzyme manufacturing process. More studies are needed for analysing the role played by transporters for subsisting the toxic chemicals. Focus on the characterization of fungal metabolites, exploring more species involved in the process, examining its chemical structure and toxicity levels would help in concluding which species can be exploited more for remediation. The role of fungal mycotoxins in bioremediation requires consideration. This information can help us in genetic engineering of the strains to improve them for their appropriate use. Their role in plastic degradation also needs to be analyzed extensively so that it may help us in some way to win the battle of enormous solid waste management. Mushroom production needs to be enhanced as their mycelium also assists in biosorption due to its large surface area.

Conclusively, much light needs to be shed on the role of macrofungi in bioremediation that remains a field to be extensively explored. The popularization of the mycoremediation methods is the demand of time with the globally rising unpredictable environmental issues.

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