Chapter

The Role of Mushrooms in Biodegradation and Decolorization of Dyes

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Abstract

Contamination of soil, water, and air by hazardous substances is the major environmental problem of today's world. Mushroom consumption has become a tradition among many people due to its richness in flavors, proteins, and some medicinal importance. But its ability to degrade/decolorize hazardous substances and dyes by secreting various enzymes or by absorption and adsorption of colors from waste substances has made them of interest for use in the field of bioremediation. Mushroom acts as a good decomposer as it degrades cellulose and lignin of plants for their growth and development. It also maintains soil health by performing the role of hyperaccumulators. This chapter focused on the mushroom-based biodegradation/decolorization of dyes and effluents released from various industries or other sources. It also emphasizes the probable mechanisms involved in mushroom-based degradation and decolorization of dyes along with their recent achievements, advancements, and future prospective.

Keywords: mushroom, biodegradation, biosorption, bioconversion, decolorization, dye, agro-industrial wastes

1. Introduction

To fulfill the demand of growing number of people, rapid industrialization and modernization not only give useful products but also release hazardous elements to nature. The release of industrial effluents and the accumulation of toxic substances into the biosphere destroy the environment by interacting with various components of the natural ecosystem [1]. The effluents released from textile industries, food processing industries, pharmaceutical industries, etc., containing various synthetic dyes, toxic heavy metals, and other wastes, directly or indirectly come in contact with water and soil and destroy water and soil properties by changing the pH, total organic carbon (TOC), biological oxygen demand (BOD), and chemical oxygen demand (COD) [1, 2]. Various types of synthetic dyes are used extensively in the field of textile industries for coloring purposes. For example in batik industries, Remazol Brilliant Blue R (RBBR) and naphthol are used as coloring agents. Remazol Brilliant Blue R is a heterocyclic compound, and its derivatives are toxic to the environment. On the other hand, naphthol is insoluble in water and is used to dye cellulosic fibers. Improper handling, carelessness, and inefficient dye waste treatments of industries are the main reasons for the contamination of soil and water [3]. The concentration of carcinogenic heavy metals like As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, etc. are relatively high in untreated industrial wastes. The rapid depletion of dissolved oxygen in water due to the presence of toxic heavy metals and other industrial wastes leads to "oxygen sag" [1]. Majority of the synthetic dyes are used in the field of textile industries, and the effluents are discharged as wastewater. The dyes or their breakdown products are hazardous they are found to be carcinogenic [4].

Remediation refers to the complete or partial removal of contaminants from the polluted sites to provide a sustainable environment. Various physical and chemical remediation technologies are developed to eliminate the pollutant from the soil and improve soil health. Higher costs, limited applications with limited opportunities, and the inability to enhance intrinsic soil health make them almost abandoned [5]. Bioremediation refers to the use of biological agents such as microbes, plants, or any other living things that help to reduce contamination to a nontoxic level or untraceable level [5]. Paul Stamets first coined the term "mycoremediation" based on the fungal detoxification of contaminated soil. He defined the term mycoremediation as a process of sequestration of contaminated soil or water by using fungi to reduce contaminants [6]. Mushrooms are sources of protein and their enzymatic machinery have the ability to degrade pollutants for their growth and developments. Thus, mushroom cultivation got much more attention in the field of decolorization and biodegradation research. Mushrooms are mostly basidiomycetes, a class of fungi which secretes a variety of extracellular enzymes for their growth and development [7]. These enzymes include laccase, lignin peroxidase (LiP), versatile peroxidase (VP), manganese peroxidase (MnP), phenoloxidases, etc. [8]. Singh reported that the lignin degradation ability of white-rot fungi is due to the presence of phenoloxidase [1]. Due to the potential role in bioremediation of various dyes, lignin, and cellulosic compounds, the white-rot fungi became a model organism for mycoremediation [1]. Due to the structural similarity of polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyl (PCB), various dyes, dioxins, and pesticides with lignin, cellulosic compounds, and with their substrates, mushroom-based mycoremediation processes got much more emphasized in the recent years [9]. This chapter focused on the mushroom-based biodegradation/decolorization of dyes and effluents released from various industries or other sources. It also emphasizes the probable mechanisms involved in mushroom-based degradation and decolorization of dyes along with their recent achievements, advancements, and future prospective.

2. Role of mushroom in decolorization of dyes

Industries like textile, food processing, chemical, leather, dyestuff, dyeing, and pharmaceutical industries release a huge number of effluents containing various types of dyes. Textile industries are thought to be leading producers of dyes, and the dyes released from industries directly penetrate into the soil and water and disturb the natural ecosystem [10]. Around 80,000 tons of dyestuff and shades are created in India. It has been assessed that 10,000 distinctive colored materials are economically accessible worldwide and the yearly generation is evaluated to be 7×10^5 metric tons [11]. In the field of textile industries, azo dyes are mostly used as a colorant agent. The presence of one or more azo groups helps to prevent the molecules from breakdown and degradation and hence persistently accumulated into the environment. The entry of industrial effluents into the water causes a drastic reduction of dissolved oxygen; as a result great environmental damage will occur [10]. The entry of dyes into the aquatic ecosystem disturbs light penetration into the deeper part; as a result, reduction of water quality, photosynthetic activity, as well as gas availability into the aquatic ecosystem is observed [6].

Different physical and chemical methods are developed for decolorization of dyes from the pollutant sites which includes absorption through activated carbon, flocculation, ion exchange, membrane filtration, etc. but due to high expensive, inefficient, and these methods also release different types of wastes which are also toxic for nature [10]. On the other hand, mushroom-based decolorization and degradation of dyes got much more research attention because it is less expensive and eco-friendly and also produces negligible amounts of wastes [6]. Due to the powerful enzymatic activities as well as high adaptability under physically harsh conditions, microbial decolorization and biodegradation is one of the most focused research areas for sustainable developments [1]. Aromatic amines, phenolics, etc. are some intermediates generated during decolorization processes which are highly toxic with low biodegradability as compared to dye. Sometimes, such intermediates inhibit the decolorization ability of bacteria. While fungi have the ability to degrade complex organic compounds and the intermediates through their extracellular enzymes secretion. On the other hand, it is thought that the large surface area of fungi has a greater ability for biodegradation [12]. The decolorization ability of dyes varies from strain to strain, and most of the studies are confined to single-strain-based degradation or decolorization of specific dyes. However, industrial effluents are a cocktail of various organic and inorganic pollutants. Considering these factors, the researcher proposed that the use of novel microbial consortium in the field of bioremediation could be a better option [13]. And many reports suggest that the microbial consortium possesses greater biodegradation ability due to their interactive effect with the contaminants [13–15]. According to Forgacs et al., the individual strain of a consortium has a specialized role for specific contaminants and may attack the different portions of dye and also has the ability to degrade the intermediate components such as phenolics and aromatic hydrocarbons produced by co-strains [16]. By using this approach, several components of the contaminants can be treated at the same time.

Biodegradation and decolorization ability of mushroom has shown a promising approach since the 1980s. There are many reports regarding the decolorization of different types of dyes by using mushrooms. Cripps et al. reported the decolorization of azo dyes by ligninolytic enzymes secreted by *Phanerochaete chrysosporium*, a white-rot fungus [17]. A similar degrading activity was later reported on another species of white-rot fungi [18]. White-rot fungi have a variety of advantages that can be utilized in the field of bioremediation. The extracellular lignin-degrading system of white-rot fungi has the ability to degrade various toxic chemicals like polyhydroxy aromatic carbons and other phenolic compounds [19]. Freitag and Morrell screened 170 fungal strains to understand the decolorization of poly R-478, a polymeric dye, through ligninolytic activity of the fungi and the existence of peroxidase and phenoloxidase activity. In the plate test, they found that the decolorization rate increased with the increase of radial growth of fungi, indicating that decolorization is directly correlated with hyphal development [20]. Reddy et al. reported that the growth of white-rot fungi through hyphal extension and hence penetration of fungal hyphae into the contaminated soil could help in bioremediation [12, 20]. While, according to Moreno-Garrido, immobilization of mushroom fungi is one of the strategies for biodegradation [21]. Yao et al. studied the decolorization of three different azo dyes by extracellular enzymes produced by *Schizophyllum* sp. F17, and they found that manganese peroxidase (MnP) played an important role in the process of decolorization [22]. The copper-containing laccase is one of the important enzymes that also play a significant role in the bioremediation of dyes. Lallawmsanga et al. screened 40 enzymes for their laccase productions and their role in decolorization of dyes. They found eight strains that have elevated levels of laccase producing ability; *P. pulmonarius* BPSM10 strain decolorizes seven dyes under the aqueous condition and can be used as an alternative biosorbent to decolorize dyes under aqueous condition [23]. Chakraborty et al. reported another white-rot fungus *Alternaria alternata* CMERI F6 having a 99.99% decolorization ability of Congo red within 48 h. The metabolites produced through HPLC and FTIR suggested that the decolorization of dye occurred through the biosorption and biodegradation process [24]. Mahmoud in 2016 studied the decolorization ability of Baker's yeast under aqueous condition. He reported that Baker's yeast can reduce the color and COD of textile effluents by 100% and 61.8% and can be used for bioremediation [25]. Another white-rot fungal strain, KRUS-G, is able to decolorize Remazol Brilliant Blue R up to 1500 ppm concentration by secreting laccase and manganese peroxidase. And it is also reported that an increase in concentration slightly decreases the hyphal growth [26].

3. Mechanism of mushroom-based decolorization of dyes

The biodegradation or decolorization of dyes mainly consists of three basic processes [1, 27]. These are as follows:

1. A slight change in additional organic molecules without changing the main structure of the compounds.

2. Fractionation of the complex structural organic molecules in such a way that the combination of the fractions could give rise to the original molecules.

3. Mineralization of the complex structural molecules, i.e., transformation of the complex molecules into the mineral forms.

It is thought that adsorption of the dyes is the primary mechanism of dye decolorization by fungus or any other biological mode of decolorization. In many reports, it was found that adsorption of dyes is the important mechanism of dye decolorization by which the transformation of dyes starts [1, 28]. Microscopic observation of the fungal cells showed that instead of fungal hyphae, fungal spores are the main dye-absorbing components [1]. Hydrophilic and hydrophobic interactions of fungi and dyestuff play a crucial role in the enhancement of dye absorption [28]. Some reports also state that when the concentration of extracellular enzymes and cell mass increased, the dye color in the medium decreased indicating that the decolorization of dyestuff is directly proportional to the cell mass as well as the extracellular enzymes produced by the fungus [1].

Mushroom-based degradation or decolorization of dyes is mainly classified into [1] biosorption and [2] biodegradation [1, 29].

3.1 Bio-sorption

Biosorption is a complex physicochemical method of biological materials that have the ability to accumulate pollutants into cellular components through adsorption, ion exchange, deposition, etc. and plays an important role in dye decolorization by fungi [1, 30]. Fu and Viraraghavan reported that the decolorization of dyes like Disperse Red I, Congo red, Acid Blue 29, and Basic Blue 9 by *Aspergillus niger* is due to the presence of carboxyl, amino phosphate group, and lipid fractions [31].

Carboxyl, amino phosphate group, and lipid fractions together act as a binding site for Congo red. While for decolorization of Basic Blue 9, carboxyls, and amino groups are the binding sides. The amino group of *Aspergillus niger* alone acts as a binding site for Acid Blue 29, whereas amino groups along with lipid fractions have the binding ability for Disperse Red I. They also reported that along with adsorption, electrostatic attraction mechanisms also have a crucial role in dye decolorization [9].

Fu and Viraraghavan from their study suggested that the adsorption efficiency could be enhanced by treating the biomass with suitable organic or inorganic molecules like formaldehyde, sulfuric acid, sodium hydroxide, calcium chloride, and sodium bicarbonate and by high temperature. Increase in temperature by autoclaving and chemical treatments by 0.1 N NaOH, 0.1 M HCl, and 0.1 M H_2SO_4 increased the biosorption. It was found that the physical treatments increased the biosorption rate of the Basic Blue 9 dye by 15 times, whereas chemical treatment with 0.1 M H_2SO_4 enhanced the rate of biosorption of Acid Blue 29 dye by 2 times. The physical treatment of autoclaving of fungal biomass could change the surface charge, and acid pretreatment enhanced the affinity of anionic dyes to bind with the fungal surface [31]. Arica and Bayramoğlu also observe the same result by autoclaving *Lentinus sajor-caju* at 100°C for 10 min; the biosorption capacity of fungal biomass *Lentinus sajor-cafju* for Reactive Red 120 dye increased [32]. A number of a research articles have been published based on the dye biosorption ability of mushroom fungi, and these are depicted in **Table 1**.

Serial number	Mushroom used	Name of the dye	Remarks	References
1.	*Ganoderma* sp.	Orange II, 10B (Blue), RS (Red)	*Ganoderma* sp. able to degrade woods, based on this fact the decolorization test against those dyes showed significant results	[33]
2.	*Agaricus bisporus*	*Basic Red 18*, Levafix Braun E-RN, Acid Red 111	Mushroom stump wastes are found to play a promising role in the decolorization of wastewater containing dyes released from various industries. Freeze-dried mushroom stumps showed higher decolorization efficiency for basic dyes, while heat-dried stumps showed greater biosorption efficiency for acidic dyes	[34]
3.	*Pleurotus ostreatus*	Malachite green, xylidine	pH plays an important role in dye decolorization. Maximum biosorption was observed at pH 3 for malachite green, while, for xylidine, the pH values varied from pH 3 to 4	[35]
4.	*Pleurotus ostreatus*	Malachite green	Biosorbant dose, time, and pH were important factors for biosorption. Ca^+ and Na^+ ions play a crucial role in biosorption. The presence of hydroxyl, carboxylic acid, phosphate, and amino group on the surface of biosorbent, i.e., *Pleurotus ostreatus*, *w*as confirmed by FTIR	[36]
5.	*Lentinus sajor-caju*	Reactive Red 120	Maximum uptake was noticed at pH 3.0 for all the fungal preparations. And highest dye uptake efficiencies were observed in heat-treated preparations followed by acid-treated, native, and base-treated preparations	[32]

Serial number	Mushroom used	Name of the dye	Remarks	References
6.	*Agaricus bisporus* and *Thuja orientalis*	Reactive Blue 49 (RB49)	Mix culture of *Agaricus bisporus* and *Thuja orientalis* showed efficient decolorization of Reactive Blue 49 (RB49) dye by biosorption. FTIR and SEM analysis confirmed the presence of hydroxyl, carboxyl, amine, and amide groups on the surface of biosorbent	[37]
7.	*Pleurotus ostreatus*	Methylene Blue	The biosorption ability of a white-rot fungi *Pleurotus ostreatus* is studied against Methylene Blue. And it was found that pH, dye concentration, and fungal biomass plays an essential role in biosorption	[37]
8.	*Agaricus bisporus*	Crystal Violet-Brilliant Green	Thermodynamic studies show that Crystal Violet-Brilliant Green adsorption by *Agaricus bisporus* is a spontaneous process. Dye-fungus interaction was studied by SEM, X-ray crystallography, and Fourier transform electron spectroscopy to understand the mechanism of dye adsorption. And it was concluded that the process is eco-friendly and economical and can be used for the cationic dye biosorption process	[38]
9.	*Agaricus bisporus* and *Thuja orientalis*	Reactive Red 45	Biosorption of Reactive Red 45 by *Agaricus bisporus* and *Thuja orientalis* is highly pH-dependent, and the process is spontaneous and exothermic. Mix culture treatment showed 100% biosorption. It can be used as an alternative mode of biosorbent for industrial dye removal	[39]
10.	*Lentinus concinnus*	Disperse Red 60	Immobilized fungal biomass of *Lentinus concinnus* has maximum biosorption at pH 6.0 and can be used for Disperse Red 60 dye removal from industrial effluents	[40]

Table 1.
Role of mushrooms in biosorption of dyes.

3.2 Biodegradation

Biodegradation is the process by which complex organic molecules are converted into its simpler forms by the action of enzymes secreted by fungi, bacteria, or any other living microorganisms [41]. A lot of studies have been carried out to understand dye degradation by mushrooms and the enzyme produced by them, and these are represented in **Table 2**. Many reports suggested that the extracellular enzymes produced by mushroom have a potential role in dye decolorization and also have degradability for non-polymeric compounds like polyhydroxy aromatic hydrocarbons, nitrotoluene, and pentachlorophenol under in vitro conditions [46]. In recent years, degradation of polymeric compounds like plastics by various types of mushrooms is also reported [51].

Serial number	Mushroom used	Name of the dye	Enzyme produced	References
1.	*Pleurotus pulmonarius BPSM10*	Malachite green	Laccase	[23]
2.	*Pleurotus ostreatus*	Remazol Brilliant Blue R	Manganese peroxidase, manganese-independent peroxidase, and phenoloxidase	[42]
3.	*P. ostreatus*, *P. sapidus*, *P. florida*	Coralene Golden Yellow, Coralene Navy Blue, and Coralene Dark Red	Laccase, manganese-dependent peroxidase (MnP), and lignin peroxidase	[43]
4.	*Pleurotus pulmonarius*	Remazol Brilliant Blue R, Congo red, Methylene Blue, and ethyl violet	Laccase and manganese peroxidase	[44]
5.	*Pleurotus ostreatus*	Acetyl Yellow G (AYG), Remazol Brilliant Blue R or Acid Blue 129 (AB129)	Dye-decolorizing peroxidase (DyP)	[45]
6.	*Lentinus edodes*	Poly-478 and Remazol Brilliant Blue R	Manganese peroxidase	[1]
7.	*Lasiodiplodia* sp.	Malachite green	Laccases	[46]
8.	*Pleurotus ostreatus*	Synthetic dye	Laccases, lignin peroxidases	[47]
9.	*Pleurotus florida*	Blue CA, Black B133, Corazol Violet SR	Laccases	[48]
10.	*Pleurotus pulmonarius*	CK, Congo red, Trypan blue, methyl green, Remazol Brilliant Blue R (RBB), methyl violet, ethyl violet, and Brilliant Cresyl Blue	Laccases	[29]
11.	*Ganoderma* sp.	Textile effluents	Laccases	[49]
12.	*Pleurotus ostreatus IBL-02*	Synthetic dye	Ligninolytic enzymes	[50]

Table 2.
Role of mushroom in biodegradation of dyes by means of enzymatic secretions.

The degradation of polycyclic aromatic carbons by cleaving a carbon-carbon single bond is an important feature of white-rot fungi [1]. The lignin-degrading enzymes of white-rot fungi such as lignin peroxidases or ligninases have a potential role to initiate oxidative depolymerization of lignin for degradation of various organo-pollutants. The ligninolytic activity of a white-rot fungi *P. chrysosporium* has the capability to degrade various industrial dyes and other toxic aromatic ring-containing compounds [52]. Various mechanisms have recently been identified for fungi-based degradation of dyes. The generation of free radicals by white-rot fungi for the degradation of various synthetic dyes or other pollutants is one of the best-known mechanisms or decolorization of dyes [1]. Due to their highly reactive nature, free radicals are able to donate or accept electrons from other chemicals, and sometimes chain reactions occur due

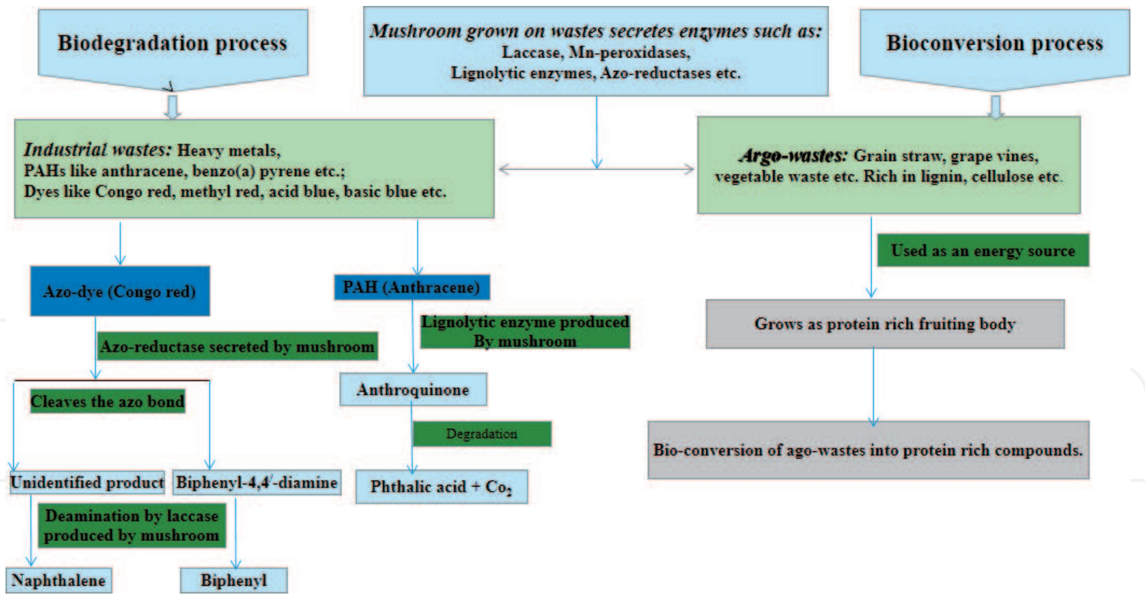

Figure 1.
Schematic representation of mushroom-based enzymatic biodegradation and bioconversion of dyes and other agro-wastes.

to donation and accepting of electrons, and also various radicals are generated along with the formation of initial radicals. These free radicals are catalyzed by peroxidase enzymes produced by white-rot fungi which play a subsequent role in the degradation process of various industrial pollutants [1, 53, 54]. The role of veratryl alcohol in azo dye degradation catalyzed by ligninase enzyme produced by white-rot fungi along with H_2O_2 was reported by Paszczynski and Crawford [55]. Peroxidases, laccases, and azoreductases are the major enzymes produced by mushrooms during the biodegradation of dyes. Azo linkage and chromophoric groups of azo dyes are reduced by the enzyme azoreductases produced by mushrooms responsible for azo dye degradation (**Figure 1**) [56]. An edible mushroom *Lentinus edodes* which produces a high amount of manganese peroxidase degrade Poly-478 and Remazol Brilliant Blue R [1]. Vyas and Molitoris reported the decolorization of Brilliant Blue R by mushroom *Pleurotus ostreatus* by secreting H_2O_2-dependent enzymes [42]. Laccase enzyme produced by *P. pulmonarius* BPSM10 showed efficient dye decolorization, especially malachite green (MG). The decolorization efficiency of *P. pulmonarius* BPSM10 was confirmed by FTIR [23].

4. Degradation of agricultural pesticides, chemical, and other wastes

Nowadays, agricultural management practices depend on the efficient management of biotic factors such as insects, pests, various diseases, weeds, etc.; otherwise, plant growth and development along with crop yields would decrease drastically. To minimize such drastic loss in crop production, there is continuous use of insecticides, pesticides, weedicides, and chemical fertilizers constantly releasing xenobiotic compounds into the environments [19, 57]. Xenobiotic compounds are not easily degraded by microbes and hence remain active in the soil and water [58]. The use of pesticides in India is considerably increasing after 2009–2010. It was reported that the consumption of pesticides in 2014–2015 is 0.29 kg/ha which is 50% higher than that in 2019–2010 [59]. According to previous reports, only 5% of the applied pesticides are effective in targeted pest management, and the rest of the pesticides are mixed with soil and water, affecting human health by interfering with the food chain [60, 61]. On the other hand, modernization, industrialization, and other anthropogenic activities continuously releasing wastes containing hazardous compounds like heavy metals, dyes, phenolic compounds, polyhydroxy aromatic hydrocarbons, etc. are also disturbing agricultural lands [19].

5. The mechanism involved in the degradation of agrochemicals and other wastes by mushroom

Mushroom-based degradation of agrochemical wastes, heavy metals, phenolics, polyhydroxy aromatic hydrocarbons, and other wastes basically involves enzymatic degradation, biosorption, and bioconversion techniques. Researchers have published a number of research articles on mushroom-based biodegradation of agronomic wastes [19, 62].

5.1. Enzymatic degradation of agricultural wastes

Mycologists and environmental researchers are giving attention to enzymatic degradation of agricultural wastes by using mushrooms. However, the proper role of enzymes in pesticide degradation is not clear. But there is some evidence suggesting that lignin-degrading enzymes are responsible for pesticide degradation. Mushrooms do not secrete pesticide-degrading enzymes in a similar manner; that is, it varies from species to species, type of condition, and other physical and chemical factors [5, 19]. Xenobiotics are chemical compounds that are found in the environment but not naturally produced in the environments. Sometimes, a naturally occurring component is also called xenobiotic when it is excessively available in the environment. Xenobiotics are not easily degradable in nature and hence actively present into the environment. Polycyclic aromatic hydrocarbons, alkanes, oil spills, azo dyes, antibiotics, dioxins, polychlorinated, chlorinated, polyaromatic compounds, etc. are major xenobiotics continuously released into the environment [63]. Microbes play a significant role in the field of biodegradation. There are some reports suggesting the involvement of mushroom fungi in the degradation process of agrochemicals such as xenobiotics, heavy metals, and other agricultural wastes by secreting various enzymes like oxidoreductases, laccases, oxygenase, and peroxidases. These enzymes can degrade the hazardous compounds by the breakdown of ester, amide, ether bonds, and sometimes the aromatic ring or the aliphatic chains of those compounds [6, 19, 64]. The concentration of hazardous compounds, reaction conditions, and the suitable sites are also responsible for the degradation of such compounds. Sometimes, xenobiotic compounds are utilized by mushrooms for their growth and development as their source of energy, carbon, nitrogen, and sulfur [6]. Some researchers reported that the ligninolytic enzyme produced by mushrooms can degrade the PAHs into mineral forms. For example, the ligninolytic enzyme produced by *P. chrysosporium* can produce anthraquinone by degrading anthracene, a PAH. Further degradation of anthraquinone can produce phthalic acid and carbon dioxide (**Figure 1**) [65]. Few examples of mushroom which have the ability to degrade agrochemical pollutants by secreting enzymes are listed in **Table 3**.

As there are so many reports on enzymatic degradation of xenobiotics, there are also some reports on the non-ligninolytic degradation of xenobiotics. Jackson et al. reported the degradation of 2,4,6-Trinitrotoluene (TNT) by *P. chrysosporium* in the absence of ligninolytic enzymes [80]. Bending et al. also reported white-rot fungal degradation of atrazine and terbuthylazine in the aqueous condition in the absence of ligninolytic enzymes [81].

Serial number	Mushroom used	Name of the pollutant	Enzyme produced	References
1.	*Pleurotus ostreatus*	Plastics	Lignocellulolytic enzymes	[66]
2.	*Lentinula edodes*	2,4-Dichlorophenol	Ligninolytic enzyme-derived vanillin	[67]
3.	*Pleurotus pulmonarius*	Radioactive cellulosic-based waste	Ligninolytic enzymes	[68]
4.	*Auricularia* sp., *Schizophyllum commune*, and *Polyporus* sp.	Malachite green	Biosorption and enzymatic degradation	[69]
5.	*Pleurotus pulmonarius*	Crude oil	Peroxidase	[70]
6.	*Coriolus versicolor*	PAHs	Laccase, manganese-dependent peroxidase, and lignin peroxidase	[71]
7.	*P. ostreatus*	Anthracene	Lignin peroxidase, laccase, and manganese peroxidase	[72]
8.	*Pleurotus ostreatus*	Green polyethylene	Laccase	[66]
9.	*Pleurotus palmonarius*, *Pleurotus tuber-regium*, *Lentinus squarrosulus*	Crude oil	Ligninolytic enzymes	[73]
10.	*Pleurotus tuber-regium*	Crude oil	Ligninolytic enzymes	[74]
11.	*Bjerkandera adusta*	PAHs, PCBs	lignin-degrading enzyme	[53]
12.	*Irpex lacteus*	PAHs, TNT, bisphenol, dimethyl, phthalate	Laccase, lignin peroxidase, manganese peroxidase, versatile peroxidase	[75]
13.	*Pleurotus ostreatus and Irpex lacteus*	PCBs	Oxidoreductases	[76]
14.	*Phanerochaete chrysosporium*	DDT, PHAs, PCBs,	Lip, MnP	[77]
15.	*Phanerochaete chrysosporium*	PAHs	Peroxidases (LiP, MnP)	[52]
16.	*Schizophyllum commune*, *Polyporus* sp.	Malachite green dye	Ligninolytic enzymes	[69]
17.	*Trametes versicolor*	Lignin, polycyclic aromatic hydrocarbons, polychlorinated biphenyl mixture, and a number of synthetic dyes	Ligninolytic enzymes	[75]
18.	*P. chrysosporium*	Styrene	Peroxidases	[78]
19.	*Pleurotus ostreatus* HP-1	Fluoranthene	Manganese peroxidase (MnP) and laccase	[79]

Table 3.
Role of mushrooms in degradation of pollutants by secreting enzymes.

Serial number	Mushroom species	Agro-industrial wastes	Results	References
1.	*V. volvacea*	Banana leaves	Improved yield and provide sustainable feed for ruminant animals	[83]
2.	*Lentinula edodes*	Wheat straw	Bioconversion of wheat straw by synthesizing lignocellulosic enzymes and increased yield.	[84]
3.	*Pleurotus sapidus*	Wheat straw, rice straw, corn stover, corncobs, sugarcane bagasse (SCB), and banana stalk (BS)	Bioconversion by producing ligninolytic and cellulolytic enzymes	[85]
4.	*Pleurotus tuber-regium*	Cotton waste, rice straw	Lipase, peroxidase, cellulase, carboxymethylcellulose enzyme activity increased	[86]
5.	*Pleurotus eous*, *Lentinus connatus*	Rice straw, banana stem, sorghum stalk	Yield increased, degradation of lignin was observed	[87]
6.	*Pleurotus florida*	Paper waste, cardboard industrial waste	High protein content was observed	[88]
7.	*Pleurotus ostreatus*	Sawdust	Temperature and pH are important factors for the growth of mushrooms	[89]
8.	*Volvariella volvacea*	Sawdust	Enzyme activity was measured, and high cellulosic activity is responsible for bioconversion	[90]
9.	*Pleurotus citrinopileatus*	Paper waste, cardboard waste	Basidiocarps are grown and having high nutrients with no genotoxicity	[91]
10.	*Pleurotus tuber-regium*	Rice straw, cocoyam peels	Yield improved with high protein content, fat content	[92]
11.	*Lentinula edodes*	Eucalyptus waste	Successful bioconversion by lignin degradation was observed. Qualitative and quantitative changes are also noticed	[93]
12.	*Lentinus tigrinus*	Wheat straw	Bioconversion of wheat straw and production of lignocellulosic enzymes are observed	[84]

Table 4.
Role of mushroom in bioconversion of agro-industrial wastes.

5.2 Bioconversion of agricultural wastes

Agro-industrial wastes are the by-products of agricultural processing industries such as grain milling industries, oilseed-processing industries, brewery industries, and fruit and vegetable processing industries. These agro-industrial wastes are rich in various nutrients and bioactive compounds. Nowadays, researchers employ attention in bioconversion of such agro-industrial wastes into some other useful components [5]. Mushroom cultivation on agro-industrial wastes is one of the most important

examples of bioconversion where fruiting bodies are used as a product [82].
The choice of agro-industrial substrates depends upon the availability of the substrates [5]. Mushroom cultivated on agro-industrial wastes is mentioned in **Table 4**. As agro-industrial wastes are rich in nutrients, mushroom-based mycoremediation of such components gives rise to protein-rich fruiting bodies by degrading such industrial wastes (**Figure 1**) [82].

6. Biosorption of heavy metals

Biosorption is defined as "the ability of biologically active i.e. living or inactive i.e. non-living or dead organisms/materials that can accumulate and concentrate heavy metals even from very dilute medium by means of adsorption, absorption, ion-exchange or by using metabolic processes" [94]. Biosorption is a complex process, depending upon different factors like temperature, pH, the concentration of the substrates, nature of the substrates, contact time, as well as the property of the host, i.e., cell wall composition, types of proteins, amino acids, lipids, etc. [8, 19, 94].

In recent years, mushroom-based biosorption for waste management is one of the important research interests. A lot of research is going on regarding mushroom-based bioremediation for the cleanup of the environment, and mushroom-based biosorption of heavy metals is an important one [5]. Few reports on mushroom-based biosorptions of heavy metals are mentioned in **Table 5**.

Serial number	Mushroom species	Pollutants	Results	References
1.	*Pleurotus sajor-caju*	Heavy metals	Absorb heavy metals from contaminated sites	[95]
2.	*Pleurotus ostreatus*	Cadmium	Mushrooms are grown on the substrate containing cadmium and absorbed cadmium by the fruiting bodies	[96]
3.	*Pleurotus tuber-regium*	Heavy metals	Mushroom species are grown in soil by mixing heavy metals and played an efficient role in bioabsorption	[97]
4.	*Flammulina velutipes*	Copper	*Flammulina velutipes* were grown in aqueous conditions containing copper and were found as an efficient bioabsorbant	[98]
5.	*Pleurotus platypus*, *Agaricus bisporus*, *Calocybe indica*	Copper, zinc, iron, cadmium, lead, nickel	Mushroom species are grown in aqueous wastes containing heavy metals (copper, zinc, iron, cadmium, lead, and nickel and were found as an efficient bioabsorbant	[99]
6.	*Fomes fasciatus*	Copper	Mushroom species showed efficient bioabsorption of copper	[100]
7.	*Agaricus bisporus*, *Lactarius piperatu*	Cadmium	*Agaricus bisporus*, Lactarius piperatu has higher cadmium removal efficiency	[101]

Table 5.
Role of mushroom in bioremediation of heavy metal pollutants by biosorption process.

7. Factors affecting the degradation

Biodegradation by means of mushroom basically depends on the survival and multiplication of mushrooms [102]. Different intrinsic and extrinsic factors play an essential role in mushroom survival and multiplication. Substrate concentration, source of nitrogen, carbon-nitrogen ratio, pH, moisture, minerals, particle size, spawning level, surfactant, etc. are important intrinsic factors, while temperature, humidity, luminosity, air composition, etc. are extrinsic factors [103]. Alteration on those factors largely affects mushroom multiplications, and ultimately mushrooms will be unable to survive [102, 103].

pH plays an essential role in mushroom growth and it varies from mushroom to mushroom. Bellettini et al. reported the pH value of 4.0–7.0 helps mycelium growth, while pH value between 6.5 and 7.0 helps basidiocarp development [103]. Velioglu and Ozturk Urek reported that pH of 6.0 gives better growth of *P. djamor* [104].

Moisture is another important factor for mushroom growth as the flow of moisture helps to transfer nutrients from mycelium to fruiting body [105]. High moisture contents cause difficulties for mycelium respiration and interpretation of the development of the fruiting body, while low moisture contents lead to the death of the fruiting body [103]. Chang and Miles reported that 50–75% of moisture contents are suitable for the growth of mushrooms [105].

8. Advantages of mushroom-based mycoremediation

Mushroom cultivation under suitable conditions can help to detoxify various types of contaminants by secreting different types of nonspecific enzymes [106]. Hyphae help to establish direct contact with the contaminants [95]. Mushroom-based bioremediation of pollutants have several advantages, which are mentioned below:

- Due to the low cost, it got much more public acceptance.
- Safe and eco-friendly technique.
- Easy and simple cultivation process.
- Low maintenance.
- Mushrooms grow faster and produce reusable end products.

9. Limitations of mushroom-based degradation

The role of mushrooms in bioremediation of environmental pollutants like industrial wastes containing dyes; heavy metals; agrochemical wastes like pesticides, herbicides, insecticides, and other xenobiotic compounds; and agro-industrial wastes like brewery wastes, grain milling wastes, and fruits and vegetable processing wastes are studied [85]. However, certain drawbacks are noticed in mushroom-based remediation. Fungi-based degradation of pesticides is a slower and incomplete process; accumulation of incomplete substrate produces various secondary metabolites that might be harmful [19]. Adaptation of the chosen mushroom species against the pollutant is another major problem of mushroom-based bioremediation [5]. Physicochemical properties of soil and climatic conditions are sometimes problematic for bulk transfer of mushroom under field conditions [107]. The use of mushrooms with beneficial bacterial strain could help to degrade pollutants at faster rates. Identification of genes that are responsible for biodegradation of pollutants and the introduction of such genes to the indigenous strain could solve the availability of capable strain under field conditions [108]. Mushrooms are famous due to their richness in proteins and flavors and also for their medicinal importance. Mushrooms cultivated into the contaminated sites or cultivated for remediation of pollutants can accumulate different types of toxic substances into their fruiting bodies. Consumption of those mushrooms could cause major health problems and sometimes may become the reason for death [109].

10. Conclusion and future prospective

Logical advancements are considered as key components for the progression of underdeveloped countries. But the majority of industries do not have a legitimate waste treatment plan and discharge an enormous amount of effluents. The accomplishment of a microbial procedure for color removal from the industrial discharge relies upon the usage of microorganisms that viably decolorize manufactured colors of various compound structures. Most of the mushroom-based degradation/decolorization of dyes and other wastes has been performed under laboratory conditions. The outcomes gotten for the most part from the research facility tests rely upon explicit development and optimization of medium, proper handling of mushroom species, and biomass. Therefore, essential works on the topic are still under investigation to assess the information on the process of implementation under field conditions. Certain species of mushroom showed efficient degradation/decolorization/mineralization of the dyes, organochemicals, and other industrial wastes either by biosorption or by enzymatic secretion. Based on those facts, proper design of the waste management process by using proper strain is an essential step. The inhibition of growth and secretion of degrading enzymes of mushrooms by the contaminants containing different form of hazardous pollutants is another major problem in mushroom-based degradation of dyes or other pollutants. Utilizing molecular tools for identification of the genes responsible for the degradation of specific dyes may be helpful for biodegradation. Genetic engineering technologies for the development of genetically modified strain for the degradation or decolorization could solve the problem. The connection among the researchers of interdisciplinary research fields like biotechnology, microbiology, chemistry, and genetic engineering could help to develop a successful technique for bioremediations.

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