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Oyster Mushroom in Bioremediation: A Review of Its Potential and Applications

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Abstract

Oyster mushrooms (*Pleurotus* spp.), a widely cultivated edible fungus, hold immense potential in the field of bioremediation due to their unique physiological and enzymatic capabilities. Bioremediation is an eco-friendly process that employs biological systems to degrade, immobilize, or transform environmental pollutants, such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), pesticides, and synthetic dyes, into less toxic or reusable forms. Oyster mushrooms stand out due to their ability to grow on diverse substrates, rapid growth rates, and secretion of ligninolytic enzymes, such as laccases and manganese peroxidases, which break down complex pollutants. Additionally, their mycelial networks exhibit biosorption properties that effectively bind and immobilize heavy metals, making them ideal candidates for mycoremediation. This review explores the mechanisms underlying the bioremediation capabilities of oyster mushrooms, focusing on enzymatic degradation of organic pollutants and biosorption of heavy metals. Furthermore, the economic and environmental advantages of using oyster mushrooms in bioremediation are discussed, including cost-effectiveness, dual benefits of waste recycling and edible mushroom production, and adaptability to various environmental conditions. The paper also highlights challenges such as enzyme specificity, scalability, and secondary metabolite toxicity. Future research directions include genetic engineering to enhance enzymatic efficiency, co-cultivation strategies with other microorganisms, and field trials to validate laboratory findings. Oyster mushrooms thus represent a sustainable, versatile, and efficient approach to addressing global pollution challenges.

Keywords: Oyster mushrooms, Bioremediation, Mycoremediation, Ligninolytic enzymes, Laccases

Introduction

Mushrooms belong to the family of Basidiomycetes, commonly known as saprophytic fungi. The fruiting body of mushrooms consists of a steam (Stipe) with and a bearing cap (Pilues), a spore-forming part (sporophore). Mushrooms uptake nutrients from the substrate/soil via specious mycelium. The age and size of the fruiting body determine the uptake of nutrients from the substrate or the soil (Gonkhom et al., 2024).

One kind of edible fungus that has been widely grown for both culinary and therapeutic uses is oyster mushrooms. Because of their special qualities—such as their rapid growth rates, broad range of substrates, and capacity to digest pollutants—researchers have recently looked at their potential in bioremediation (Gonkhom et al., 2024). Concern over an efficient system for managing biological waste is rising on a global scale. Every year, a variety of activities, including the petroleum industry, agriculture, agro-industries, and municipal solids, produce waste in their unprocessed, original form. Large amounts of organic pollutants and garbage are produced annually and discharged into the environment (soil and water) (Bogan et al., 1999). Waste comes in a variety of forms; the three main categories are solid, liquid, and semi-solid. Without adequate recycling, these wastes are burned or dumped, endangering human health, polluting the environment, and ultimately causing global warming (Isikhuemhen et al., 2003). Because heavy metal and/or organic pollutant-contaminated soils may not be suitable for both agricultural output and human health, they are typically abandoned for several years. Although several techniques have been employed to remove heavy metals, none are as successful as biological techniques (such as using bacteria, fungi, algae, and plants) because they are costly, ineffective at removing heavy metals entirely, and still far more expensive ("Mushrooms in the Bio-Remediation of Wastes from Soil," 2019).

Therefore, it is imperative that a wide range of pollutants and wastes be removed from the environment in order to support the sustainable growth of our civilization with minimal negative effects on the environment (Dasetima-Altraide et al., 2021). Given the scope of the issue and the absence of a workable solution, a quick, economical, and environmentally conscious cleanup technique is desperately needed (C. O., 2012).

Figure 1: *Pleurotus ostreatus* (Oyster Mushroom)

Source: (Anjana & Savita, 2017)

Numerous creatures, including plants, fungi, algae, and bacteria, have been employed to break down contaminants and purify our surroundings (Cateni et al., 2022). On the other hand, Fungi are the best biological decomposers, which are essential in turning these wastes into useful products. Because of their physiological adaptability, they can be found in a wide range of environments, including those with acidic pH, temperature, oxygen concentrations, salinity, and heavy metal concentrations. Because they contain extracellular enzymes, mushrooms have been demonstrated to break down a variety of waste materials, including organic and inorganic contaminants, turning them into nutrient-dense, flavorful, and high-quality food (Abah et al., 2024). As a result, oyster mushrooms could be a promising fungus for bioremediation of the environment. (Chugh et al., 2022)

Mushrooms are macrofungi with a distinctive fruiting body, are unique biota which assemble their food by secreting degrading enzymes and decomposing the complex organic materials on which they grow (the substrate) to generate simpler compounds for their nutrition (Valverde et al., 2015). These substrate materials are usually by-products from industry, households and agriculture, usually considered wastes. These wastes, if carelessly disposed of in the surrounding environment by dumping or burning, will lead to serious environmental pollution and consequently cause health hazards. However, they are resources in the wrong place at a particular time, and mushroom cultivation can harness this waste/resource for its benefit (Beelman et al., 2019).

Notable nutraceutical products with numerous health advantages can also be made from mushrooms. They give individuals another high-quality vegetable and add high-quality proteins, minerals, and vitamins to the diet, all of which can directly improve people's health and fitness. The bioactive substances that can be extracted from therapeutic mushrooms would strengthen people's immune systems and raise their standard of living (Teja et al., 2023). The protein level of edible mushrooms is comparable to that of meat, eggs, and milk, making them extremely nutrient-dense (Abah et al., 2024). Mushrooms contain a high concentration of critical amino acids nearly identical to the human body's needs. Mushrooms have no cholesterol and are readily digested (Elsayed et al., 2014).

Because they can turn lignocellulosic waste materials into food, feed, and fertilizer, mushrooms are incredibly environmentally friendly. It can be grown in containers such as jars, basins, trays, plastic bags, and other materials by creating artificially regulated circumstances. They can be harvested three to four weeks after spawning since they grow quickly. As a result, growing mushrooms is a short-term, important biological decomposer essential to turning waste into useful products. The leftover spent substrate from mushroom harvesting, which contains countless mushroom threads (collectively called mycelia) that have been biochemically changed by the enzymes in the mushrooms into a simpler and easier-to-digest form, can be used to make biogas, bio-fertilizer to improve soil fertility, and more palatable animal feed (Iyekekpolor, 2024).

Myco-filtration (using mycelia to filter water or mycelia are used as a filter to remove toxic materials and microorganisms from water in the soil), myco-forestry (using mycelia to restore forests), myco-remediation (using mycelia to eliminate toxic waste), and myco-pesticides (using mycelia to control insect pests) are some of the ways that mushroom mycelia can significantly contribute to the restoration of damaged environments (myco-restoration). These techniques can produce a healthy ecosystem with no harm after using fungi (Kumar & Sagar, 2023).

They can also function as an efficient bio-sorbent of harmful metals and break down and turn lignocellulosic materials into nourishment for humans. Certain heavy metals, like lead, cadmium, and others, can accumulate in higher amounts in mushrooms than in green plants (Dasetima-Altraide et al., 2021).

Because heavy metal and/or organic pollutant-contaminated soils may not be suitable for both agricultural output and human health, they are typically abandoned for several years. Furthermore, using chemical treatments to excavate and remove contaminated soil is relatively expensive and environmentally hazardous. However, mushroom growing, a biological process that turns waste into useful products, is economical and environmentally friendly. Therefore, it is envisaged that promoting mushroom farming will be a significant endeavour that could clean up contaminated land (El-Ramady et al., 2022).

Mechanisms of Bioremediation by Oyster Mushrooms

One of the most promising options for reducing environmental pollutants brought on by heavy metals, which have detrimental effects on both the environment and human health, is bioremediation. It is the process of breaking down or eliminating hazardous organic pollutants at the molecular level, such as those found in pesticides, oil spills, and industrial waste, and turning them into safer substitutes (Dasetima-Altraide et al., 2021).

The ultimate goal of bioremediation is the full mineralization of contaminants, i.e. their transformation to CO_2, H_2O, N_2, HCl, etc. Heavy metal and radioactive cations, of course, cannot be decomposed but have their solubility lowered or reduced, e.g. by a change in oxidation state, so that they become less harmfully in the ground or might be removed by phytoremediation or myco-remediation, which involves harvesting the fungus (Damodaran et al., 2011). *Pleurotus ostreatus* can degrade Benzo[a]pyrene, but the presence of heavy metal cations and mediators such as vanillin and 2,2'-azinobis-(3- ethylbenzothiazoline-6-sulfonate) highly influence the degradation process.

The uptake rate of nutrients from the waste by mushrooms is affected by the nature of substrates, pH, and species of mushrooms and, to a certain extent, the genus, biomass, and the presence or absence of heavy metals. The remediation process also varies according to the species; some species degrade the waste easily and quickly, while others can slowly break down the waste. The remediation rate becomes maximal when there is a good supply of nutrients in the soil, e.g. N, P, K and other essential inorganic elements.

Table 1: Heavy Metal Content in Sporocarp of *pleurotus* specie

Mushroom specie	Metal content (Accumulated metals in sporocarp, mg/kg of dry weigh	Reference
Pleurotus sp.	Pb (3.24), Cd (1.18), Hg (0.42), Cu (13.6), Mn (6.27), Zn (29.8), Fe (86.1). Pb (0.11), Cd (0.55), Hg (0.31), Fe (48.6),Cu (5.0), Mn (10.3), Zn (19.3)	(Damodaran et al., 2011)

The bioremediation potential of oyster mushrooms is primarily driven by their enzymatic systems, including ligninolytic enzymes such as laccases, manganese peroxidases, and versatile peroxidases. These enzymes break down complex pollutants into simpler, less toxic compounds. Additionally, oyster mushrooms possess mycelial networks capable of binding and immobilizing heavy metals and other inorganic pollutants, reducing their mobility and bioavailability (Damodaran et al., 2011).

Applications of Oyster Mushrooms in Bioremediation

1. Degradation of Organic Pollutants

Oyster mushrooms have effectively broken down various organic pollutants, including polycyclic aromatic hydrocarbons (PAHs), pesticides, and dyes.

- Polycyclic Aromatic Hydrocarbons (PAHs): PAHs are persistent organic pollutants with carcinogenic and mutagenic properties. Pleurotus ostreatus has been shown to degrade PAHs such as anthracene, phenanthrene, and pyrene through oxidation and ring-opening mechanisms mediated by ligninolytic enzymes (Damodaran et al., 2011). Recent studies have shown that *P. ostreatus* can degrade a variety of polycyclic aromatic hydrocarbons (PAH) It can degrade PAH in non-sterile soil both in the presence and in the absence of cadmium and mercury (Dasetima-Altraide et al., 2021; El-Ramady et al., 2022). It has been reported to catalyze the humification of anthracene, benzo (a) pyrene and flora in two PAH – PAH-contaminated soils from a manufactured gas facility and an abandoned electric cooping plant (Bogan et al., 1999). The white-rot fungus, *P. tuber-regium* is another fungus examined for its ability to ameliorate crude oil polluted soil. Isikhuemhen et al., (2003) reported that the fungus had the ability to ameliorate crude oil-polluted soil, and the resulting soil sample supported seed germination and seedling growth of Vigna unguiculata. They reported a significant improvement in percentage germination, plant height and root elongation (Damodaran et al., 2011).

- Pesticides: Organophosphates and chlorinated pesticides are degraded by oyster mushrooms, which metabolize these compounds into less harmful substances. Laccase and peroxidase enzymes play a central role in this process (Isikhuemhen et al., 2003).

- Synthetic Dyes: Oyster mushrooms effectively degrade synthetic dyes used in textile and paper industries. The ligninolytic enzymes cleave the dye molecules' chromophores, reducing their colour and toxicity (Bogan et al., 1999).

2. Heavy Metal Removal

Oyster mushrooms exhibit remarkable biosorption capacity for heavy metals like cadmium, lead, mercury, and arsenic. The cell wall of the fungal mycelium contains functional groups such as carboxyl, hydroxyl, and amino groups, which bind to metal ions (Damodaran et al., 2011). Mycelial biomass can be a biofilter to remove metals from contaminated water and soil.

Advantages of Using Oyster Mushrooms in Bioremediation

- Cost-effectiveness: Cultivating oyster mushrooms requires minimal investment and can utilize agricultural waste as a substrate.

- Eco-friendly Approach: Unlike chemical and physical remediation methods, mycoremediation using oyster mushrooms does not introduce additional environmental pollutants.

- Dual Benefits: Alongside pollutant degradation, oyster mushrooms produce edible fruiting bodies, offering an additional economic incentive.

- Wide Range of Applications: Oyster mushrooms can adapt to various environmental conditions and degrade a broad spectrum of pollutants.

Challenges and Limitations

Despite their potential, the use of oyster mushrooms in bioremediation faces certain challenges:

- Specificity of Enzyme Activity: The efficiency of pollutant degradation varies depending on the type and concentration of the pollutant.

- Field Application Constraints: Scaling up laboratory findings to field conditions requires overcoming environmental variables and ensuring consistent performance.

- Persistence of Secondary Metabolites: The degradation of pollutants may produce intermediate compounds, some of which may remain toxic.

Future Perspectives

Research into enhancing the bioremediation capabilities of oyster mushrooms is ongoing. Key areas of focus include:

- Genetic Engineering: Manipulating the fungal genome to overexpress specific ligninolytic enzymes could improve degradation efficiency.

- Co-cultivation Strategies: Combining oyster mushrooms with other microorganisms, such as bacteria, could create synergistic effects for more efficient pollutant degradation.

- Nanotechnology Integration: Functionalizing fungal biomass with nanoparticles could enhance biosorption capacity and catalytic activity.

- Pilot Studies: Conducting large-scale trials in real-world contaminated sites will be crucial for validating laboratory findings.

Conclusion

The use of oyster mushrooms (*Pleurotus* spp.) in bioremediation represents a promising, sustainable solution for tackling environmental pollution. Their ability to degrade organic pollutants, immobilize heavy metals and recycle lignocellulosic wastes into valuable byproducts underscores their significance in achieving ecological balance and supporting waste management efforts. Unlike conventional remediation techniques, oyster mushrooms offer a cost-effective and environmentally friendly alternative that aligns with circular economy principles by turning pollutants into resources.

Despite the remarkable potential of oyster mushrooms in pollution control, challenges such as pollutant specificity, environmental variability in field applications, and the persistence of intermediate metabolites remain. Addressing these limitations through advances in biotechnology, such as genetic engineering and microbial consortia, could significantly enhance their remediation efficiency. Furthermore, integrating oyster mushrooms into large-scale bioremediation initiatives, supported by governmental policies and public awareness, is essential for practical implementation.

Oyster mushrooms not only contribute to environmental restoration but also offer economic benefits through the production of nutritious, edible fruiting bodies and biofertilizers. This dual benefit positions them as a key agent in bridging the gap between environmental sustainability and socio-economic development. Future efforts should focus on optimizing their bioremediation applications while ensuring scalability and environmental safety. Through continued research and innovation, oyster mushrooms could play a pivotal role in restoring ecosystems and mitigating the adverse impacts of pollution globally.

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