

Mycoremediation: An Insight to Cleanup of Pollutants

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Abstract Over the years, there has been a rise in the release of pollutants into the environment. Pollutants from heavy metals, synthetic dyes, and plastics pose significant threats to ecosystems and human health. Mycoremediation involves the use of fungi for degrading or neutralizing contaminants within the environment. Mycoremediation, employing fungi to degrade or neutralize contaminants, offers a sustainable and effective solution to this environmental challenge. Several processes such as biosorption, bioaccumulation, and biovolatilization utilise fungi's ability to adsorb, accumulate, and transform pollutants, offering sustainable and cost-effective solutions for environmental cleanup. They also possess specific enzymatic systems that alter them to break down complex pollutants into less harmful forms. Complex pollutants like dyes, heavy metals and synthetic plastics are changed into less toxic forms. Enzymes such as Lacasse, Peroxidases, Cutinases and Lipases are secreted by some fungal isolates that help in the remediation of toxic pollutants. Various fungal species, from the genus *Penicillium*, *Pleurotus*, *Trichoderma*, *Fusarium*, *Zalerion*, *Lasioidiplodia*, *Papiliotrema*, and *Aspergillus* have been identified for their ability to remediate pollutants efficiently. Mycoremediation processes are cost-effective and environmentally friendly cleanup solutions. This paper reviews the potential of mycoremediation in addressing heavy metal, dye, and plastic pollution, highlighting its significance as a sustainable alternative to conventional cleanup methods.

Keywords: Mycoremediation, Pollutants, Plastics, Heavy metals and Dyes.

I. Introduction

Pollutants are substances or contaminants introduced into the environment that cause adverse effects on ecosystems, human health, or other organisms [1]. They can be of various types, including heavy metals, dyes, and synthetic plastics. These pollutants often originate from industrial activities, agriculture, transportation, and household sources, leading to widespread environmental contamination [2]. Deposition of heavy metal to the environment poses a grievous threat to human health and any biodiversity. Copper, Arsenic, Mercury, Lead, Chromium, Cadmium, Nickel and Silver are few of the

usually found metals at various contaminated land site [3]. These metals get into the soil and water by different activities of natural habitats and humans. Volcanic eruption, Soil erosion, and weathering of the earth's crust are few natural ways of pollution with heavy metal. The ways of anthropogenic include waste material from the industries like fertilizer, textiles, paints and even metal parts. Leaded petrol, mining, electronic wastes, fungicides, preservatives, insecticides, and combustion of fossils are some other origins of heavy metals [4]. After the metal leaching into the environment, they eventually get into the human body through the consumption of contaminants from water and food. At reduced concentration, some of these metals play a necessary role in different physiological and metabolic activities, but above

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a threshold limit, they have deleterious effects. Many of these metals are known as carcinogens and mutagens. They also spoil the proper performance of the heart, spleen, liver, kidney, and reproductive systems [5].

Among many forms of pollutants, dye is one of the momentous units, which is much stabilized in water and baffling for biodegradation owing to their synthetic ancestry and compound's molecular structure [6]. The worldwide annual estimate of dye production is above 7×10^5 tons with over 100,000 are commercially obtainable dyes whereas about 15% of these are wasted during the operational handling and 20% wasted as industrial effluents [7; 8]. Important magnitude of practical applications using dyes have been identified in many industries including dyestuffs, textile dyes, plastic, paper and pulp, tannery, rubber, paint, and electroplating manufacturers. The dyes prime consumers are the textile industries which are responsible for production of substantive complexity and volume of colored effluents [9]. Dyes are also utilized in food, petroleum industries, pharmaceuticals, and cosmetics as additives [10]. Basically, dyes are organic compounds corresponding with a compound aromatic structure of molecules giving materials the firm color and radiant which is difficult for biodegradation [11;12]. Dyes are categorized into two divisions which are synthetic and natural dyes. The synthetic dyes are principally engaged in different fields of high-tech application in numerous industries. These are also utilized in drafting the ground water through the determination of the activated sludge and sewage surface area [13] Dye is considered very hazardous with toxicity, carcinogenicity, and mutagenicity, therefore increases the demand for biochemical oxygen and its aquatic sources which is a critical health warning for humans

[14]. A dye concentration of about 1.0 mg/L in clean water could disperse color significantly and should be carefully consumed by humans [15].

Synthetic plastics have already become unmissable ware in human active lives, and dependency on these materials increases [16]. Plastic is versatile, low cost, durable, and low weight making it a valuable asset for a broad scope of applications [17]. 368 Mt (million tonnes) of plastics were produced worldwide in the year 2019. Regrettably, 8 Mt of plastics always ends up within the ocean yearly, adding to the tremendous garbage patch with a surface area of about 1.6 million square kiloMetres [18]. It is expected that by 2050, 1,800 Mt of synthetic plastic will be produced, in which 1,200 Mt will end up as plastic waste in the environment [19]. The leading challenge with plastics is that 90% production consists of synthetic polymers such as polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), polystyrene (PS), polyurethane (PU) and polyvinyl chloride (PVC) which take numerous years to decay [20]. For example, PET water bottle, plastic straw, PS foam and single-use diaper are estimated to have lifespan above 200 and beyond 5000 years in the surroundings respectively. So much inherent degradation resistance coupled with unrestrained usage has now become a major concern due to plastic waste disposal [21]. Plastic known as non-biodegradable and/or has a slow rate of degradation thus resulting to persisted nature accumulation of plastic waste. Accordingly, this causes grave environmental interests for marine and terrestrial life, but also for human health and vegetation [22]. For example, the depletion of underground water reserve through plastic waste blocking the air and water from moving through the earth. Moreover, when plastic is overexposed to sunlight, small toxic parts are discharged to contaminate the soil and water [23].

Various methods are exploited for the treatment of pollutants, such as physical, biological and chemical approaches. Physical methods like reverse osmosis, ion exchange and filtration are effective to remove pollutants like heavy metals from water but may be energy-intensive and expensive [24]. Chemical treatments involve processes like oxidation-reduction and chemical precipitation, but they may alter soil properties and have limited efficacy at low pollutant concentrations. Mycoremediation offers a promising alternative for pollutant cleanup. Mycoremediation involves the use of fungi for degrading or neutralizing contaminants within the environment. Fungi have unique enzymatic systems that allow them to break down complex pollutants like dyes and synthetic plastics into less toxic forms [25]. Mycoremediation processes such as biosorption, bioaccumulation, and biovolatilization utilize fungi's ability to absorb, accumulate, and transform pollutants, offering sustainable and cost-effective solutions for environmental cleanup [26]. Among the fungal species here mentioned are usually degrade various

types of pollutants e.g *Penicillium simplicissimum*, *Fusarium solani*, *Zalerion maritimum*, *Lasioidiplodia theobromae*, *Papiliotrema laurentii*, *Aspergillus flavus*, *Aspergillus fumigatus*, *Penicillium chrysogenum*, *Pleurotus ostreatus*, and *Aspergillus tubingensis* and WRF (White Rot Fungi) [27;28] This review revealed the significance of mycoremediation lies in its ability to provide sustainable and environmentally friendly solutions to pollution problems. By harnessing the natural abilities of fungi, mycoremediation offers a cost-effective alternative to traditional cleanup methods [29].

A. Pollutants

i. Heavy Metals

Heavy metals, characterized by their atomic weights falling within the range of 63.5 to 200.6

and possessing high densities of approximately 5 g/cm³, constitute a significant concern in various environmental and biological contexts [30]. While some of these metals play crucial roles in biological functions within organisms when present within certain limits [31], excessive intake of certain heavy metals can lead to severe health implications. To categorize their health significance, heavy metals are broadly classified into four main groups. Firstly, there are essential heavy metals including copper (Cu), iron (Fe), chromium (Cr), manganese (Mn), cobalt (Co), and zinc (Zn). These metals are termed micronutrients, are vital for various physiological processes but can pose hazards if consumed beyond recommended levels. Secondly, there are heavy metals like aluminum (Al), barium (Ba), lithium (Li), and zirconium (Zr) that are not essential for biological functions. Thirdly, tin (Sn) and aluminum (Al) are deemed less hazardous heavy metals compared to others [32]. Finally, there are toxic heavy metals, for example cadmium (Cd) and mercury (Hg), which can cause severe health issues even at reduced exposure levels.

ii. Dye

Dyes are essentially organic or inorganic compounds with synthetic and compound unsaturated aromatic molecular structures with fulfilled characteristics like fastness, intensity, color, and wholly soluble in aqueous media [33]. Owing to the chemical composition of the synthetic dyes making them to have the fading up resistance in light, water, and variety of chemicals, also the acidic properties make them stronger and steadier to biodegrade when it intermingled with water [34].

Application of synthetic dyestuffs in large-scale applications causes intractable problems in the environment. Because of the high strength of colors in water, dyes are vividly seen to human

eye even in a very little concentration that might even be highly insufferable on aesthetic grounds [35]. Aside aesthetic issues, the sunlight assimilation by the dyestuffs in water can have grave environmental interest [36]. The dyes are precisely carcinogenic and toxic due to the presence of aromatics and metals that block the light penetration therefore affecting the biological metabolic activity through disconcerting the aquatic photosynthetic activities. In different cases of microbiological or fish species, dyes are known to be really toxic/mutagenic and teratogenic [37]. In addition, it accounts for stern damage to human health status including brain, kidney, liver, and reproductive dysfunctions. Reactive dyes are extremely water-soluble and chemically stable with colored effluent which is a captious challenge for the environment. Azo dyes are exceedingly toxic in water owing to the existence of toxic amines but anthraquinone dye is very stable and its degradation takes a very long time [38].

iii. Synthetic Plastic

Polyolefins are made from polymerising olefins, such as propylene isoprenes, butenes and ethylene [39]. Their energy efficiency, recyclability and mechanical flexibility make them highly demanded material that is used in our daily life [40]. Examples of polyolefins which are considered most produced plastics are Low-Density Polyethylene (LDPE) and High-Density Polyethylene (HDPE). This two polyethylene (PE) consist of long ethylene monomers chains and have a broad scope of applications [40] (Dziadowiec *et al.*, 2023). Generally, HDPE has a low grade of branching, subsequently having glass transition temperature (T_g), crystallinity and high melting point (T_m). These attributes make it very resistant and strong to moisture. Hence, HDPE is used in food packaging,

detergent bottles, toys, and textile industries [41]. Contrarily, LDPE has a high degree of branching, resulting in a less flexible material [41]. Polypropylene (PP) is another kind of polyolefin and known as the second most produced plastic. It is one of the more durable with high heat resistance, that is often used in products with the ability to withstand heat. More examples include nonabsorbable sutures, plastic pressure pipe systems, plastic tubs, and food packaging [42]. Also, another frequent polymer is Polyethylene terephthalate (PET), that is composed of ethylene glycol and terephthalic acid (TPA). Because of its semi crystallinity, this plastic is lightweight but strong making it an enthralling material to be used in synthetic fibre, microwavable packaging and drink bottles [43].

Furthermore, Polyvinyl Chloride (PVC) is made of chloroethyl monomers repetition and is usually used in construction. Due to its resistivity to chemicals and weathering, as well as its rigidity and hardness, it is the perfect material in used for window frames, plumbing pipes, data cables and flooring [44]. Furthermore, Polystyrene (PS), also called Styrofoam, is made from aromatic styrene monomers. Described as tough, lightweight, and rigid having ability to insulate well thus used in cups, cutlery, packaging foam and CDs [45]. Polyurethane (PUR) is acquired by compressing polyisocyanate and polyols, to be either polyethers or polyesters (PS-PUR) that are linked together by urethane (carbamate). This plastic is mostly utilized in surface coatings and foams, for example thermal insulation foams and cushioning foams [46].

B. Heavy Metals Mycoremediation

The application of fungi to mitigate heavy metal pollution has garnered considerable attention for its potential as an eco-friendly and cost-effective

conceptualization. Numerous studies have investigated various aspects of this area, shedding light on the diverse capabilities of different fungal species in metal removal and tolerance (Table 1).

The potency of mixture of fungal isolates, including *Penicillium chrysogenum*, *Rhizopus oryzae*, and *Aspergillus niger* for removing copper (II) and zinc (II) from aquatic environments was examined [47]. Their findings highlighted optimal biosorption conditions such as temperature, contact time, initial metal concentration, and pH [48], focused on fungal strains' tolerance to heavy metals, particularly Cu, Pb, and Fe, demonstrating their exceptional capacity even at concentrations exceeding permissible limits. The mechanisms underlying arbuscular mycorrhizal fungus (AMF) inoculation's role in enhancing cadmium (Cd) tolerance in *Phragmites australis*, revealing selective Cd distribution at subcellular levels was investigated [49]. Xie et al. [50], explored the use of Cd-resistant fungi, such as *Aspergillus aculeatus*, to improve Cd tolerance in bermudagrass, indicating promising results in mitigating Cd stress. Qayyum et al. [51], isolated fungal strains from heavy metals contaminated soil and assessed their biosorption capacity, identifying specific fungal isolates with high biosorption potential. Panda et al. [52], highlighted indigenous fungal strains' capability, such as *Aspergillus fumigatus*, in removing heavy metals from contaminated environments. Falandysz [53] explored the potential of the *Coprinus comatus* (Shaggy Ink Cap) as a bio-extractor of mercury (Hg) in polluted soils. Kapahi and Sachdeva [54] emphasized the biosorption potential of *Pleurotus* species due to their extensive biomass. Zhang et al. [55], investigated the earthworm gut fungus *Trichoderma brevicompactum* QYCD-6 for its ability to digest and remove heavy metals, highlighting

its promising potential for heavy-metal wastewater remediation. Cárdenas González et al. [56], studied the biosorption of cobalt (Co) by fungal biomasses, demonstrating the efficacy of certain fungal strains, such as *Paecilomyces* sp., in removing Co from aqueous solutions. Mohammadian et al. [57] et al., evaluated fungal populations' tolerance and biosorption capacity in metal-contaminated soils, identifying *Trichoderma harzianum* as the most tolerant and effective against Pb, Cd, and Cu. Bano et al. [58] investigated obligatory halophilic fungi for their biosorption of various heavy metals, highlighting the potential of strains like *Aspergillus flavus* and *Sterigmatomyces halophilus* in metal removal. García-Hernández et al. [59], emphasized the significant tolerance of filamentous fungi to heavy metals, underscoring their importance as potential agents for environmental remediation. Iram et al. [60], isolated heavy metal-resistant fungi and assessed their biosorption capacity, indicating the potential of *Aspergillus* spp. in removing metals like Cu(II) and Pb(II) under optimal conditions.

Allothman et al. [61], developed fungi-based biosorbents for heavy metal removal, demonstrating their effectiveness in treating contaminated wastewater. Hassan et al. [62], conducted bioremediation on the site for heavy metal-impacted landfill soil using a fungal consortium, showcasing enhanced metal removal efficiency compared to untreated soil. Khan et al. [63], isolated indigenous metallotolerant fungal strains and evaluated their efficiency in removing Pb and Hg from contaminated soil samples, suggesting their potential for remediation applications.

C. Mycoremediation of Dye

Various methodologies for dye decolorization using white rot fungi have been explored in

Table 1: Summary of the Fungi used in mycoremediation of heavy metals.

Fungi Used	Name of Metals Degraded	Results	References
<i>Aspergillus niger</i> , <i>Penicillium chrysogenum</i> , <i>Rhizopus oryzae</i>	Zinc (II), Copper (II)	Mixed fungal isolates showed capacity to remove Zn(II) and Cu(II) from aquatic environments, with optimal conditions identified for maximum removal.	[47]
<i>Fomitopsis meliae</i> , <i>Trichoderma ghanense</i> , <i>Rhizopus microspores</i>	Copper (Cu), Lead (Pb), Iron (Fe), Cadmium (Cd), Arsenic (As)	Fungal strains exhibited exceptional metal tolerance, even exceeding permissible limits for contaminated soils, suggesting potential for bioremediation.	[48]
<i>Arbuscular mycorrhizal fungus</i> (AMF)	Cadmium (Cd)	AMF inoculation alleviated Cd toxicity in plants and induced selective Cd distribution at subcellular levels, enhancing Cd tolerance of plants.	[49]
<i>Aspergillus aculeatus</i>	Cadmium (Cd)	<i>A. aculeatus</i> improved Cd tolerance and reduced Cd transportation in Bermudagrass, suggesting its potential for Cd remediation.	[50]
<i>Aspergillus flavus</i> , <i>Rhizomucor pusillus</i>	Lead (Pb), Chromium (Cr), Cadmium (Cd)	Resistant fungal isolates demonstrated high biosorption capacity for Pb, Cr, and Cd, suggesting their potential for removal of high concentration metals from industrial effluents and soil.	[51]
<i>Penicillium sp.</i> , <i>Aspergillus fumigatus</i> , <i>Aspergillus sp.</i> , <i>Penicillium adametzi</i> , <i>Aspergillus niger</i>	Chromium (Cr)	Indigenous fungi, especially <i>A. fumigatus</i> , showed potential for Cr removal from contaminated environments.	[52]
<i>Coprinus comatus</i>	Mercury (Hg)	<i>C. comatus</i> showed potential as a bio-extractor and bioindicator of Hg pollution in soils.	[53]
<i>Pleurotus</i> species	Various heavy metals	<i>Pleurotus</i> species demonstrated high biosorption potential for heavy metals, indicating their suitability for bioremediation applications.	[54]
<i>Trichoderma brevicompactum</i> QYCD-6	Copper (Cu), Chromium (Cr), Cadmium (Cd), Zinc (Zn), Lead (Pb)	<i>T. brevicompactum</i> QYCD-6 showed promising potential for heavy metal removal from wastewater via biosorption, with mechanisms involving bioaccumulation and functional group interactions.	[55]
<i>Paecilomyces sp.</i> , <i>Penicillium sp.</i> , <i>Aspergillus niger</i>	Cobalt (Co)	Fungal biomasses showed high biosorption efficiency for Co(II) removal, with <i>Paecilomyces</i> sp. exhibiting the best results.	[56]

recent research (Table 2). Wang et al. [64], investigated the decolorization of Congo red by the white-rot fungus *Ceriporia lacerata*, revealing the influence of various factors on the decolorization rate. Upadhyay and Przysaś [65], also found *Pleurotus ostreatus* capable of decolorizing Anthanthrone Red and Disazo Red dye solutions, with differing toxicity outcomes. Usha et al. [66], compared the decolorization efficiency of *Stereum ostrea* and *Phanerochaete chrysosporium*, highlighting the former's superior performance. Przysaś et al. [67], studied the result of solid supports on fungal immobilization and decolorization efficiency. Zuleta-Correa et al. [68], and Jiménez et al. [69], investigated decolorization using banana peels and corncobs as adsorbents, respectively. Bankole et al. [70], demonstrated the effectiveness of a fungal consortium in dye decolorization. Chicatto et al. [71], utilised solid-state fermentation (SSF) for dye decolorization. Adak et al. [72] employed fungal laccase enzymes for dye decolorization. Contato et al. [73], studied decolorization using *Pleurotus pulmonarius* cultures. Dinh Giap et al. [74] examined lignin peroxidase enzyme extracts for dye decolorization. Xu et al. [75], optimized laccase production using Response Surface Methodology. Vršanská et al. [76], investigated dye decolorization using immobilized laccases. Oliveira et al. [77] employed lignin peroxidases for dye decolorization. Lastly, Diorio et al. [78], innovated a novel bioreactor system for efficient dye decolorization.

D. Mycoremediation of Synthetic Plastics

In the realm of mycoremediation, a strategy utilizing fungi to mitigate plastic pollution (Table 3), Gao et al. [79], identified *Alternaria alternata* FB1 as a fungus competent of thriving on polyethylene (PE) film. This strain exhibited proficient degradation of PE, inducing conspicuous perforations on the plastic surface.

Furthermore, treatment for 28 days with strain FB1 notably reduced the relative crystallinity degree of PE from 62.79% to 52.02%.

In a study by Sangale et al. [80], the isolation of elite polyethylene-degrading fungi from the rhizosphere soil of *Avicennia marina* was done. Screening 109 fungal isolates from various eco-geographical regions on the West Coast of India, they assessed polyethylene degradation at different pH levels. Notably, *Aspergillus sydowii* strain PNP15/TS and *Aspergillus terreus* strain MANGF1/WL emerged as most effective degraders, identified through morphological and molecular analyses. De Silva et al. [81], focused on identifying proficient fungal degraders of polyethylene (LDPE) with low density. Isolating fungi out of partially degraded LDPE collected in Kaduwela, Sri Lanka, they found *Fusarium* sp. isolate PS3 initiating degradation by breaking carboxylic and aldehyde bonds. *Fusarium* sp., *Penicillium* sp., and *Aspergillus niger*, identified through ITS region sequencing, exhibited colonization on LDPE films, offering potential as inoculants for accelerated LDPE degradation.

Paço et al. [27], evaluated *Zalerion maritimum*'s response in different duration of exposure to PE pellets in medium with a minimal growth. They observed a decrease in both the size and mass of pellets, indicating *Z. maritimum*'s ability to utilize PE and contribute to microplastic biodegradation with minimal nutrient requirements. Zhang et al. [55] also isolated the *Aspergillus flavus* strain PEDX3 which is a PE-degrading fungus from the gut contents in the wax moth *Galleria mellonella*. PEDX3 effectively degraded high-density polyethylene (HDPE) microplastic particles into lower molecular weight products, demonstrating its potential for HDPE microplastic particle remediation. Verma and Gupta et al. [82], demonstrated significant LDPE biodegradation

Table 2: Summary of mycoremediation of dye using white-rot fungi

Fungi Used	Dye	Results	References
<i>Ceriporia lacerate</i>	Congo red	Optimal conditions: 30°C, pH 8; >90% decolorization rate; Transformation into more toxic compounds observed.	[64]
<i>Pleurotus ostreatus</i>	Anthanthrone Disazo Red	Red, <i>P. ostreatus</i> more efficient in Anthanthrone Red; Toxic metabolites observed; Importance of toxicity assays.	[65]
<i>Stereum ostrea</i> , <i>Phanerochaete chrysosporium</i>	Crystal violet	<i>S. ostrea</i> more efficient; Suggests potential for undiscovered fungi.	[66]
<i>Polyporus picipes</i> RWP17, <i>Gloeophyllum odoratum</i> DCa, <i>Pleurotus ostreatus</i> BWPH,	Evans blue, Brilliant green	Impact of solid support on decolorization; Fast and complete decolorization observed.	[67]
<i>Pleurotus ostreatus</i> , <i>Trametes versicolor</i> , <i>Pleurotus pulmonarius</i>	Basic Red 46	Decolorization percentages ranging from 60-70%; Utilization of agricultural waste for decolorization.	[68]
<i>Trametes versicolor</i> , <i>Pleurotus pulmonarius</i>	Allura red, Tartrazine	>90% decolorization in pure cultures; Consortium achieved >60% decolorization.	[69]
<i>Daldinia concentrica</i> , <i>Xylaria polymorpha</i>	Common bean husk	Consortium achieved >95% decolorization; Reduced toxicity of metabolites observed.	[70]
<i>Ganoderma lucidum</i> EF 31	Remazol Brilliant blue	Utilization of SSF for dye decolorization.	[71]
<i>Pseudolagarobasidium acaciicola</i> LA 1	Reactive black 5, Remazol brilliant blue R,	Variation in efficiency among dyes; Importance of enzyme extracts.	[72]
<i>Pleurotus pulmonarius</i>	Remazol brilliant blue (RBBR), Green bromocresol, Methyl red, Ethyl violet, Methyl violet, Methyl green, Methylene blue, Congo red, Poly R-478, Bromophenol blue, and Brilliant Blue Reafix BFNG	Some dyes achieved >80% decolorization; Importance of exploring various dyes.	[73]
<i>Lentinus squarrosulus</i> MPN12	Porocion Brilliant blue HGR, Acid red 299, Acid Blue 62, Acid Blue 281, Acid Blue 113, Acid red 266,	Variable decolorization efficiency observed; Influence of substrate on enzyme production.	[74]
<i>Trametes versicolor</i>	Malachite green	RSM optimized laccase production; High decolorization rate achieved.	[75]
<i>Fomes fomentarius</i> , <i>Trametes versicolor</i>	Malachite green, Bromothymol blue, Methyl red	Promising potential of CLEAs in dye decolorization; High decolorization percentages achieved.	[76]
<i>Pleurotus ostreatus</i> , <i>Ganoderma lucidum</i>	Remazol brilliant blue R	Immobilization on carbon nanotubes; Increased enzyme activity observed.	[77]
<i>Trametes versicolor</i>	Azo dye xyldine, Triphenylmethane Malachite Green	Novel bioreactor system; High efficiency in decolorization observed.	[78]

by *A. flavus* and *A. terreus* in both soil and synthetic media, providing promising prospects for LDPE degradation under environmental conditions without supplementary treatments. Chien et al. [83], isolated two elite fungal strains; *Aspergillus fumigatus* L30 and *Aspergillus terreus* HC, capable of degrading PBSA films, with *A. terreus* exhibiting superior degradation ability, advancing our understanding of PBSA biodegradation. Dharshni and Kanchana [84], assessed the degradable activity of *Aspergillus fumigatus* and *Xylaria* sp. on LDPE strips, observing pH variations indicative of degradation potential. Munir et al. [3] reported LDPE weight reductions of 5.13% and 6.63% by *Trichoderma viride* (RH03) and *Aspergillus nomius* (RH06), respectively, after 45 days of cultivation. de Oliveira et al. [85], investigated the extrusion cycles impact on degradation of a polypropylene/poly (butylene adipate-co-terephthalate)/thermoplastic starch blend inoculated with the *Aspergillus* sp. and *Penicillium* sp., observing changes in film hydrophilicity and morphology due to thermo-mechanical degradation.

Antipova et al. [86], assessed the biodegradation of various polyesters by mesophilic fungal strains, identifying *Paragyodontium album* and *Aspergillus calidoustus* as efficient degraders, with implications for environmental degradation of these materials. Lü et al. [87] explored endophytic fungi from *Nepenthes ampullaria* capable of degrading polyurethane (PUR) polymers, with three isolates closely related to *Pestalotiopsis* showing promising PUR degradation capabilities.

Oviedo-Anchundia et al. [88] analyzed the biodegradation of polyurethane, polystyrene, and polyethylene by Antarctic filamentous fungi, with *Penicillium* spp. demonstrating significant degradation, particularly in aged plastics. Ren et

al. [89], isolated a *Fusarium solani* strain capable of degrading polyurethane and polyurethane propellant binder, highlighting its potential for eco-friendly treatment of explosive materials. Osman et al. [90], isolated an *Aspergillus* sp. strain capable of degrading polyurethane films, suggesting its application in plastic-contaminated environments. Chaudhary and Vijayakumar [91], observed polystyrene weight loss during incubation with *Mucor* sp. and *Cephalosporium* sp., emphasizing their potential for polystyrene degradation. Satti et al. [92], identified *Penicillium oxalicum* strain SS2 capable of degrading polyesters within 36-48 hours, presenting a promising solution for plastic-contaminated environments. Vivi et al. [93], observed significant biodegradation of polycaprolactone (PCL) films by *Chaetomium globosum* ATCC 16021, highlighting its potential for plastic waste management. Chaudhary et al. [94], demonstrated the degradation power of *Thermomyces lanuginosus* on pre-treated LDPE films under laboratory conditions, suggesting its potential for LDPE biodegradation. Spina et al. [95], observed strong oxidation processes and modification in PE film morphology induced by *Fusarium oxysporum*, *Purpureocillium lilacinum*, and *Fusarium falciforme* highlighting their potential for PE biodegradation without the need for pretreatment.

II. Conclusion

Pollution of the environment has become a menace to society. Other methods of remediation have a resultant effect on the environment either by leaving a more toxic residue or changing the pollutants to a more toxic form. Hence, mycoremediation emerges as a promising strategy for mitigating pollution from heavy metals, synthetic dyes, and plastics. Fungi possess specific enzymatic systems that

Table 3: Summary of mycoremediation of synthetic plastics

Fungi Used	Plastics Degraded	Results	Author
<i>Alternaria alternata</i> FB1	Polyethylene (PE) film	Efficient degradation of PE film; formation of numerous holes; reduced relative crystallinity degree from 62.79% to 52.02%.	[79]
<i>Aspergillus terreus</i> , <i>Aspergillus sydowii</i> , BAYF5, PNPF15	PE (Polyethylene)	Screening of efficient polythene deteriorating fungi; weight reduction (58.51%); tensile strength reduction (94.44%).	[80]
<i>Penicillium sp.</i> , <i>Fusarium sp.</i> , <i>Aspergillus niger</i>	LDPE (Low-Density Polyethylene)	LDPE degradation by <i>Fusarium sp.</i> , <i>Aspergillus sp.</i> , <i>Penicillium sp.</i> ; identification via ITS region sequencing.	[81]
<i>Zalerion maritimum</i>	Polyethylene (PE) pellets	<i>Z. maritimum</i> utilizes PE, resulting in mass and size decrease of pellets; potential contribution to microplastic biodegradation.	[27]
<i>Aspergillus PEDX3</i> <i>flavus</i>	High-Density Polyethylene (HDPE) microplastic particles	Degradation of HDPE into lower molecular weight particles; potential application for PE MPP remediation.	[55]
<i>Aspergillus terreus</i> , <i>Aspergillus flavus</i>	Low-Density Polyethylene (LDPE)	Biodegradation of LDPE in soil and synthetic medium; weight loss percentages (14.3% - 30.6%).	[82]
<i>Aspergillus terreus</i> HC, <i>Aspergillus fumigatus</i> L30	Polybutylene succinate adipate (PBSA)	Isolation of elite fungal strains for PBSA degradation; <i>A. terreus</i> showed better degradation ability.	[83]
<i>Aspergillus fumigatus</i> , <i>Xylaria sp.</i>	Low-Density Polyethylene (LDPE)	pH variation in the culture media containing LDPE strips; indicating LDPE degradation.	[84]
<i>Trichoderma viride</i> , <i>Aspergillus nomius</i>	Low-Density Polyethylene (LDPE)	Weight reduction of LDPE films by 5.13% - 6.63% after 45 days of cultivation.	[3]
<i>Aspergillus sp.</i> , <i>Penicillium sp.</i>	Polypropylene/poly (butylene adipate-co-terephthalate)/thermoplastic starch blend	Changes in hydrophilicity and film morphology after degradation by fungi; thermo-mechanical degradation favors fungal deposition.	[85]
<i>Aspergillus</i> , <i>Fusarium</i> , <i>Penicillium</i> , <i>Parengyodontium</i>	Poly-ε-caprolactone (PCL), Poly-L-lactide (PLA), poly-D,L-lactide (DL-PLA)	Selection of mesophilic fungal strains for PCL and PLA biodegradation; colonization of DL-PLA films observed.	[86]
<i>Pestalotiopsis isolates</i>	Polyurethane (PUR) polymers	Efficient degradation of PUR by isolates; potential for bioremediation of E-waste plastics.	[87]
<i>Penicillium</i> , <i>Geomyces</i> , <i>Mortierella</i> <i>species</i>	Polyurethane, polystyrene, polyethylene	Biodegradation of aged plastics by fungal strains; <i>Penicillium spp.</i> showed highest degradation percentage.	[88]
<i>Fusarium solani</i> H14	Polyurethane (PU), PUPB	Colonization and degradation of PU and PUPB; production of degradative enzymes.	[89]
<i>Aspergillus sp.</i> S45	Polyurethane (PU)	PU degradation by <i>Aspergillus sp.</i> ; potential for plastics-contaminated environment treatment.	[90]
<i>Cephalosporium sp.</i> , <i>Mucor sp.</i>	Polystyrene (PS)	Weight loss percentages of PS by fungal strains; analysis of by-products and molecular weight.	[91]
<i>Penicillium oxalicum</i> SS2	poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), Poly(3-hydroxybutyrate) (PHB)	Efficient degradation of PHBV and PHB by <i>P. oxalicum</i> SS2 in various environments.	[92]
<i>Chaetomium globosum</i> ATCC 16021	Polycaprolactone (PCL), polyvinyl chloride (PVC)	Significant PCL biodegradation observed; minimal PVC degradation.	[93]
<i>Thermomyces lanuginosus</i>	Low-Density Polyethylene (LDPE)	Weight reduction and thermal stability increase in LDPE after incubation with <i>T. lanuginosus</i> .	[94]
<i>Fusarium oxysporum</i> , <i>Fusarium falciforme</i> , <i>Purpureocillium lilacinum</i>	Polyethylene (PE)	Strong oxidation processes and morphological changes in PE film; potential for PE biodegradation.	[95]

allow them to degrade or neutralize contaminants effectively. Various fungal species have demonstrated their ability to remediate pollutants through with processes, for example biosorption, biovolatilization and bioaccumulation. Enzymes produced by these fungi also assist in the clean-up of the environment. By harnessing the natural abilities of fungi, mycoremediation offers a cost-effective and sustainable alternative to traditional cleanup methods. Further research and implementation of mycoremediation technologies such as producing the enzymes on large scale, speeding up the different processes of mycoremediation are promising ways to address environmental pollution effectively and promote a healthier, more sustainable future

- [1] Das, S., Sultana, K. W., Ndhlala, A. R., Mondal, M., & Chandra, I. "Heavy Metal Pollution in the Environment and Its Impact on Health: Exploring Green Technology for Remediation." *Environmental Health Insights*, vol 17, 2023, pp. 11786302231201259.
- [2] Oyewusi, H. A., Wahab, R. A., & Huyop, F. "Dehalogenase-producing halophiles and their potential role in bioremediation". *Marine Pollution Bulletin*, vol 160, 2020, pp. 111603.
- [3] Munir N, Jahangeer M, Bouyahya A, El Omari N, Ghchime R, Balahbib A, Aboulaghras S, Mahmood Z, Akram M, Ali Shah SM, (2022)" Heavy Metal Contamination of Natural Foods Is a Serious Health Issue": A Review. *Sustainability*. vol 14, no 1, 2022, pp 161.
- [4] Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M. R., & Sadeghi, M. "Toxic Mechanisms of Five Heavy Metals: Mercury, Lead, Chromium, Cadmium, and Arsenic". *Frontiers in Pharmacology*, vol 12, 2021, pp. 643972.
- [5] Alengebawy, A., Abdelkhalek, S. T., Qureshi, S. R., & Wang, M. Q. "Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants: Ecological Risks and Human Health Implications". *Toxics*, vol.9, no 3, 2021, pp. 42.
- [6] Tripathi, M., Singh, S., Pathak, S., Kasaudhan, J., Mishra, A., Bala, S., Garg, D., Singh, R., Singh, P., Singh, P. K, "Recent strategies for the remediation of textile dyes from wastewater: A systematic review". *Toxics*, vol 11, no 11, 2023, pp. 940.
- [7] Oyewusi, H. A., Wahab, R. A., Akinyede, K. A., Albadrani, G. M., Al-Ghadi, M. Q., Abdel-Daim, M. M., Ajiboye, B.O. & Huyop, F. Bioinformatics analysis and molecular dynamics simulations of azoreductases (AzrBmH2) from *Bacillus megaterium* H2 for the decolorization of commercial dyes". *Environmental Sciences Europe*, vol 36, no 1, 2022, pp 31.
- [9] Dassanayake, R. S., Acharya, S., & Abidi, N. "Recent Advances in Biopolymer-Based Dye Removal Technologies". *Molecules*, vol 26, no 15, 2021, pp. 4697.
- [10] Lis, K., & Bartuzi, Z. "Plant food dyes with antioxidant properties and allergies—Friend or enemy?" *Antioxidants*, vol 12, no 7, 2023, pp. 1357.
- [11] Patel, H., Yadav, V. K., Yadav, K. K., Choudhary, N., Kalasariya, H., Alam, M. M., Gacem, A., Amanullah, M., Ibrahim, H. A., Park, J.-W., "A recent and systemic approach towards microbial biodegradation of dyes from textile

- industries". *Water*, vol 14, no 19, 2022, pp. 3163.
- [12] Oyewusi, H. A., Adedamola Akinyede, K., Wahab, R. A., Susanti, E., Syed Yaacob, S. N., & Huyop, F. "Biological and molecular approaches of the degradation or decolorization potential of the hypersaline Lake Tuz Bacillus megaterium H2 isolate". *Journal of Biomolecular Structure and Dynamics*, vol. 42, no 12, 2024, pp. 6228-6244.
- [13] Periyasamy, A. P. "Recent advances in the remediation of textile-dye-containing wastewater: Prioritizing human health and sustainable wastewater treatment". *Sustainability*, vol. 16, no 2, 2024, pp. 495.
- [14] Alsukaibi, A. K. D. "Various Approaches for the Detoxification of Toxic Dyes in Wastewater". *Processes*, vol 10, no 10, 2022, pp. 1968.
- [15] Yhon, J., Mendoza, J., Osorio, E., & Domínguez, M. P. "Continuous removal of dyes from wastewater using banana-peel bioadsorbent: A low-cost alternative for wastewater treatment." *Sustainability*, vol. 15, no 13, 2023, pp. 9870.
- [16] Khoaele, K. K., Gbadeyan, O. J., Chuniell, V., & Sithole, B. "The Devastation of Waste Plastic on the Environment and Remediation Processes: A Critical Review". *Sustainability*, vol 15, no 6, 2023, pp. 5233.
- [17] Ahmed, S., & Ali, M. "Potential applications of different forms of recycled plastics as construction materials—A review". *Engineering Proceedings*, vol 53, no 1, 2023, pp. 5.
- [18] Diggle, A., & Walker, T. R. "Environmental and economic impacts of mismanaged plastics and measures for mitigation". *Environments*, vol 9, no 2, 2022, pp. 15.
- [19] Maitlo, G., Ali, I., Maitlo, H. A., Ali, S., Unar, I. N., Ahmad, M. B., ... Bhat, M. A. (2022). "Plastic Waste Recycling, Applications, and Future Prospects for a Sustainable Environment". *Sustainability*, vol 14, no 18, 2022, pp. 11637.
- [20] Saleem, J., Moghal, Z. K. B., Shakoor, R. A., & McKay, G. "Sustainable Solution for Plastic Pollution: Upcycling Waste Polypropylene Masks for Effective Oil-Spill Management". *International Journal of Molecular Sciences*, vol 24, no 15, 2023, pp. 12368.
- [21] Landrigan, P. J., Raps, H., Cropper, M., Bald, C., Brunner, M., Canonizado, E. M., ... Dunlop, S. "The Minderoo-Monaco Commission on Plastics and Human Health". *Annals of Global Health*, vol 89, no 1, 2023, pp. 23.
- [22] Lv, S., Li, Y., Zhao, S., & Shao, Z. "Biodegradation of Typical Plastics: From Microbial Diversity to Metabolic Mechanisms". *International Journal of Molecular Sciences*, vol 25, no 1, 2024, pp. 593.
- [23] Kehinde, O., Ramonu, O. J., Babaremu, K. O., & Justin, L. D. "Plastic wastes: environmental hazard and instrument for wealth creation in Nigeria". *Heliyon*, vol 6, no 10, 2020, pp. e05131.
- [24] Hama Aziz, K. H., Mustafa, F. S., Omer, K. M., Hama, S., Hamarawf, R. F., & Rahman, K. O. "Heavy metal pollution in the aquatic environment: Efficient and low-cost removal approaches to eliminate their toxicity: A review". *RSC Advances*, vol 13, no 26, 2023, pp. 17595–17610.

- [25] Latif, W., Ciniglia, C., Iovinella, M., Shafiq, M., & Papa, S. "Role of white rot fungi in industrial wastewater treatment: A review". *Applied Sciences*, vol 13, no 14, 2023, pp. 8318.
- [26] Tufail, M. A., Iltaf, J., Zaheer, T., Tariq, L., Amir, M. B., Fatima, R., ... Ayyub, M. "Recent advances in bioremediation of heavy metals and persistent organic pollutants: A review". *Science of The Total Environment*, vol 850, 2022, pp. 157961.
- [27] Paço, A., Duarte, K., da Costa, J. P., Santos, P. S. M., Pereira, R., Pereira, M. E., Freitas, A. C., Duarte, A. C., & Rocha-Santos, T. A. P. "Biodegradation of polyethylene microplastics by the marine fungus *Zalerion maritimum*". *The Science of the total environment*, vol 586, 2017, pp. 10–15.
- [28] Ekanayaka, A. H., Tibpromma, S., Dai, D., Xu, R., Suwannarach, N., Stephenson, S. L., Dao, C., & Karunarathna, S. C. "A review of the fungi that degrade plastic". *Journal of Fungi*, vol 8, no 8, 2022, pp. 772.
- [29] Radhakrishnan, A., Balaganesh, P., Vasudevan, M., Natarajan, N., Chauhan, A., Arora, J., Ranjan, A., Rajput, V. D., Sushkova, S., Minkina, T. "Bioremediation of Hydrocarbon Pollutants: Recent Promising Sustainable Approaches, Scope, and Challenges". *Sustainability*, vol 15, no 7, 2023, pp. 5847.
- [30] Bano, A., Hussain, J., Akbar, A., Mehmood, K., Anwar, M., Hasni, M. S., Ullah, S., Sajid, S., & Ali, I. "Biosorption of heavy metals by obligate halophilic fungi". *Chemosphere*, vol 199, 2018, pp. 218–222.
- [31] Dhami, N. K., Emmanuella, M., Quirin, C., & Mukherjee, A. "Carbonate biomineralization and heavy metal remediation by calcifying fungi isolated from karstic caves". *Ecological Engineering*, vol 103, 2017, pp. 106–117.
- [32] Gajewska, J., Floryszak-Wieczorek, J., Sobieszczuk-Nowicka, E., Mattoo, A., & Arasimowicz-Jelonek, M. "Fungal and oomycete pathogens and heavy metals: An inglorious couple in the environment." *IMA Fungus*, vol 13, no 1, 2022, pp. 1–20.
- [33] Tejada-Tovar, C., Villabona-Ortíz, Á., & Ortega-Toro, R. "Removal of metals and dyes in water using low-cost agro-industrial waste materials". *Applied Sciences*, vol 13, no 14, 2023, pp. 8481.
- [34] Javaid, R., & Qazi, U. Y. "Catalytic Oxidation Process for the Degradation of Synthetic Dyes: An Overview". *International Journal of Environmental Research and Public Health*, vol 16, no 11, 2019, pp. 2066.
- [35] Ardila-Leal, L. D., Poutou-Piñales, R. A., Pedroza-Rodríguez, A. M., & Quevedo-Hidalgo, B. E. "A Brief History of Colour, the Environmental Impact of Synthetic Dyes and Removal by Using Laccases." *Molecules* (Basel, Switzerland), vol 26, no 13, 2021, pp. 3813.
- [36] Nair, V. K., Selvaraju, K., Samuchiwal, S., Naaz, F., Malik, A., & Ghosh, P. "Phycoremediation of synthetic dyes laden textile wastewater and recovery of bio-based pigments from residual biomass: An approach towards sustainable wastewater management". *Processes*, vol 11, no 6, 2023, pp. 1793.
- [37] Ali, A. E., Chowdhury, Z. Z., Devnath, R., Ahmed, M. M., Rahman, M. M., Khalid, K.,

- Wahab, Y. A., Badruddin, I. A., Kamangar, S., Hussien, M. "Removal of Azo Dyes from Aqueous Effluent Using Bio-Based Activated Carbons: Toxicity Aspects and Environmental Impact". *Separations*, vol 10, no 9, 2023, pp. 506.
- [38] Pham, V. H. T., Kim, J., Chang, S., & Bang, D. "Investigating bio-inspired degradation of toxic dyes using potential multi-enzyme producing extremophiles". *Microorganisms*, vol 11, no 5, 2023, pp. 1273.
- [39] Sauter, D. W., Taoufik, M., & Boisson, C. "Polyolefins, a Success Story". *Polymers*, vol 9, no6, 2017, pp. 185.
- [40] Wieser, M., Schaur, A., Unterberger, S. H., & Lackner, R. "On the Effect of Recycled Polyolefins on the Thermorheological Performance of Polymer-Modified Bitumen Used for Roofing-Applications". *Sustainability*, vol 13, no 6, 2021, pp. 3284.
- [41] Salakhov, I. I., Shaidullin, N. M., Chalykh, A. E., Matsko, M. A., Shapagin, A. V., Batyrshin, A. Z., Shandryuk, G. A., & Nifant'ev, I. E. "Low-Temperature Mechanical Properties of High-Density and Low-Density Polyethylene and Their Blends". *Polymers*, vol 13, no 11, 2021, pp. 1821.
- [42] Mohanan, N., Montazer, Z., Sharma, P. K., & Levin, D. B. "Microbial and Enzymatic Degradation of Synthetic Plastics". *Frontiers in Microbiology*, vol 11, 2020, pp. 580709.
- [43] Benyathiar, P., Kumar, P., Carpenter, G., Brace, J., & Mishra, D. K. (2022). "Polyethylene terephthalate (PET) bottle-to-bottle recycling for the beverage industry: A review". *Polymers*, vol 14, no 12, 2022, pp. 2366.
- [44] Lewandowski, K., & Skórczewska, K. "A Brief Review of Poly(Vinyl Chloride) (PVC)" Recycling. *Polymers*, vol 14, no 15, 2022, pp. 3035.
- [45] Capricho, J. C., Prasad, K., Hameed, N., Nikzad, M., & Salim, N. "Upcycling polystyrene". *Polymers*, vol 14, no 22, 2022, pp. 5010.
- [46] Ivdre, A., Abolins, A., Sevastyanova, I., Kirpluks, M., Cabulis, U., & Merijs-Meri, R. "Rigid Polyurethane Foams with Various Isocyanate Indices Based on Polyols from Rapeseed Oil and Waste PET". *Polymers*, vol 12, no 4, 2020, pp. 738.
- [47] Tahir, A., Lateef, Z., Abdel-Megeed, A., Sholkamy, E. N., & Mostafa, A. A. "In vitro compatibility of fungi for the biosorption of zinc(II) and copper(II) from electroplating effluent". *Current Science*, vol 112, no 4, 2017, pp. 839–844.
- [48] Oladipo, O. G., Awotoye, O. O., Olayinka, A., Bezuidenhout, C. C., & Maboeta, M. S. "Heavy metal tolerance traits of filamentous fungi isolated from gold and gemstone mining sites". *Brazilian Journal of Microbiology*, 2017, pp. S1517838216306840.
- [49] Huang, X., Wang, L., Zhu, S., Ho, S.-H., Wu, J., Kalita, P. K., & Ma, F. "Unraveling the effects of arbuscular mycorrhizal fungus on uptake, translocation, and distribution of cadmium in *Phragmites australis* (Cav.) Trin. ex Steud". *Ecotoxicology and Environmental Safety*, vol 149, 2018, pp. 43–50.
- [50] Xie, Y., Luo, H., Dua, Z., Hua, L., & Fu, J. "Identification of cadmium-resistant fungi

- related to Cd transportation in bermudagrass [*Cynodon dactylon* (L.) Pers.].” *Chemosphere*, vol 117, 2014, pp. 786–792.
- [51] Qayyum, S., Khan, I., Meng, K., Zang, X., Zhao, Y., Gu, Q., & Peng, C. “Bioaccumulation of heavy metals from aqueous solution using indigenous fungal isolates”. *Indian Journal of Geo-Marine Sciences*, vol 45, no 4, 2016, pp. 499–507.
- [52] Panda, S. S., Sahoo, K., Muduli, S. D., Sahoo, G., Ahemad, M. D. J., Nayak, B. B., & Dhal, N. K. “Chromium-tolerant indigenous fungal strains from industrial effluents of Anugul District, Odisha, India”. *Biolife*, vol 2, no 2, 2014, pp. 634–640.
- [53] Falandysz, J. “Mercury bio-extraction by fungus *Coprinus comatus*: A possible bioindicator and mycoremediator of polluted soils?” *Environmental Science and Pollution Research International*, vol 23, no 8, 2016, pp. 7444–7451.
- [54] Kapahi, M., & Sachdeva, S. “Mycoremediation potential of *Pleurotus* species for heavy metals: a review”. *Bioresources and Bioprocessing*, vol 4, no 1, 2017, pp. 32.
- [55] Zhang, J., Gao, D., Li, Q., Zhao, Y., Li, L., Lin, H., Bi, Q., & Zhao, Y. “Biodegradation of polyethylene microplastic particles by the fungus *Aspergillus flavus* from the guts of wax moth *Galleria mellonella*”. *The Science of the Total Environment*, vol 704, 2020, pp. 135931.
- [56] Cárdenas González, J. F., Rodríguez Pérez, A. S., Vargas Morales, J. M., Martínez Juárez, V. M., Rodríguez, I. A., Cuello, C. M., ... Muñoz Morales, A. “Bioremoval of Cobalt(II) from Aqueous Solution by Three Different and Resistant Fungal Biomasses”. *Bioinorganic Chemistry and Applications*, vol 2019, 2019, pp. 8757149.
- [57] Mohammadian, E., Babai Ahari, A., Arzanlou, M., Oustan, S., & Khazaei, S. H. “Tolerance to heavy metals in filamentous fungi isolated from contaminated mining soils in the Zanjan Province, Iran”. *Chemosphere*, vol 185, 2017, 290–296.
- [58] Bano, A., Chen, X., Prasongsuk, S., Akbar, A., Lotrakul, P., Punnapayak, H., ... & Ali, I. “Purification and characterization of cellulase from obligate halophilic *Aspergillus flavus* (TISTR 3637) and its prospects for bioethanol production”. *Applied Biochemistry and Biotechnology*, vol 189, 2019, pp. 1327–1337.
- [59] García-Hernández, M. A., Villarreal-Chiu, J. F., & Garza-González, M. T. “Metallophilic fungi research: An alternative for its use in the bioremediation of hexavalent chromium.” *International Journal of Environmental Science and Technology*, vol 14, 2017, pp. 2023–2038.
- [60] Iram, S., Shabbir, R., Zafar, H., ... (2015). “Biosorption and Bioaccumulation of Copper and Lead by Heavy Metal-Resistant Fungal Isolates”. *Arabian Journal for Science and Engineering*, vol 40, 2015, pp. 1867–1873.
- [61] Alothman, Z. A., Bahkali, A. H., Khiyami, M. A., Alfadul, S. M., Wabaidur, S. M., Alam, M., & Alfarhan, B. Z. “Low-cost biosorbents from fungi for HMs removal from wastewater”. *Separation Science and Technology*, vol 55, 2020, pp. 1766–1775.
- [62] Hassan, A., Pariatamby, A., Ossai, I. C., & Hamid, F. S. “Bioaugmentation assisted

- myco-remediation of HM and/metalloid landfill contaminated soil using consortia of filamentous fungi.” *Biochemical Engineering Journal*, 2020, pp. 107550
- [63] Khan, I., Ali, M., Aftab, M., Shakir, S., Qayyum, S., Haleem, K. S., ... Tauseef, I. “Mycoremediation: a treatment for heavy metal-polluted soil using indigenous metallotolerant fungi.” *Environmental Monitoring and Assessment*, vol 191, 2019, pp. 622.
- [64] Wang, N., Chu, Y., Zhao, Z., & Xu, X. “Decolorization and degradation of Congo red by a newly isolated white rot fungus, *Ceriporia lacerata*, from decayed mulberry branches”. *International Biodeterioration & Biodegradation*, vol 117, 2017, 236-244.
- [65] Upadhyay, R., & Przysaś, W. “Decolorization of two dyes using white rot fungus (BWPH) strain and evaluation of zootoxicity of post-process samples. Architecture, Civil Engineering”, *Environment*, vol 15, no 3, 2022, pp. 87-94.
- [66] Usha, K. Y., Dhar, A., Ridham, Patil, S., & Kumar, K. P. “Decolorization of triphenylmethane dye by white-rot fungi”. *Indian Journal of Advances in Chemical Science*, vol 7, no 3, 2019, pp. 65-69.
- [67] Przysaś, W., Zablocka-Godlewska, E., & Grabińska-Sota, E. “Efficiency of decolorization of different dyes using fungal biomass immobilized on different solid supports” Use of white rot fungi in the degradation of an azo dye from the textile industry”. *DYNA*, vol 83, 2018, pp. 128.
- [69] Jimenez, S., Velasquez, C., Mejia, F., Arias, M., & Hormaza, A. “Comparative studies of pure cultures and a consortium of white-rot fungi to degrade a binary mixture of dyes by solid-state fermentation and performance at different scales.” *International Biodeterioration & Biodegradation*, vol 145, 2019, pp. 104772.
- [70] Bankole, P., Adedotun, A., & Govindwar, S. “Biodegradation of a monochlorotriazine dye, cibacron brilliant red 3B-A in solid-state fermentation by wood-rot fungal consortium, *Daldinia concentrica* and *Xylaria polymorpha*”. *International Journal of Biological Macromolecules*, vol 120, 2018, pp. 19-27.
- [71] Chicatto, J. A., Rainert, K. T., Gonçalves, M. J., Helm, C. V., Altmajer-Vaz, D., & Tavares, L. B. B. (2018). “Decolorization of textile industry wastewater in solid state fermentation with Peach-Palm (*Bactris gasipaes*) residue”. *Brazilian Journal of Biology = Revista Brasileira de Biologia*, vol 78, no 4, 2018, pp. 718–727.
- [72] Adak, A., Tiwari, R., Singh, S., Sharma, S., & Nain, L. “Laccase Production by a Novel White-Rot Fungus *Pseudolagarobasidium acaciicola* LA 1 Through Solid-State Fermentation of Parthenium Biomass and Its Application in Dyes Decolorization”. *Waste and Biomass Valorization*, vol 7, no 1, 2016, pp. 9550
- [73] Contato, A., Inácio, F., Brugnari, T., Araujo, C., Maciel, G. M., Haminiuk, C., Peralta, R., & Souza, C. (2020).” Solid-state fermentation with orange waste: optimization of Laccase production from *Pleurotus pulmonarius* CCB-20 and decolorization of synthetic dyes”. *Acta Scientiarum Biological Sciences*, vol 42, 2020, pp. 2020.
- [74] Dinh Giap, V., Huu Nghi, D., Huu Cuong, L., & Thu Quynh, D. “Lignin peroxidase
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- from the white-rot fungus *Lentinus squarrosulus* MPN12 and its application in the biodegradation of synthetic dyes and lignin". *BioResources*, vol 17, no 3, 2022, pp. 4480-4498
- [75] Xu, L., Sun, K., Wang, F., Zhao, L., Hu, J., Ma, H., & Ding, Z. "Laccase production by *Trametes versicolor* in solid-state fermentation using tea residues as substrate and its application in dye decolorization". *Journal of Environmental Management*, vol 270, 2020, pp. 110904.
- [76] Vršanská, M., Voběrková, S., Jimenez Jimenez, A. M., Strmiska, V., & Adam, V. "Preparation and optimization of cross-linked enzyme aggregates using native isolate white rot fungi *Trametes versicolor* and *Fomes fomentarius* for the decolourization of synthetic dyes". *International Journal of Environmental Research and Public Health*, vol 15, no 1, 2018, pp. 23.
- [77] Oliveira, S. F., da Luz, J. M. R., Kasuya, M. C. M., Ladeira, L. O., & Junior, A. C. "Enzymatic extract containing lignin peroxidase immobilized on carbon nanotubes: Potential biocatalyst in dye decolourization". *Saudi Journal of Biological Sciences*, vol 25, no 4, pp. 651-659.
- [78] Diorio, L. A., Fréchou, D. S., & Levin, L. N. "Removal of dyes by immobilization of *Trametes versicolor* in a solid-state micro-fermentation system." *Revista Argentina de Microbiología*, vol 53, no 1, 2021, pp. 3-10.
- [79] Gao, R., Liu, R., & Sun, C. "A marine fungus *Alternaria alternata* FB1 efficiently degrades polyethylene". *Journal of Hazardous Materials*, vol 431, 202, pp. 128617.
- [80] Sangale, M. K., Shah Nawaz, M., & Ade, A. B. "The potential of fungi isolated from the dumping sites mangrove rhizosphere soil to degrade polythene." *Scientific Reports*, vol 9, no 1, 2019, pp. 5390.
- [81] De Silva JKA, Jayasekera GAU, Nanayakkara CM. "Identification of potential fungal degraders of low-density polyethylene (LDPE)" *J Sci.* vol 10, no 2, 2019, pp. 1–10.
- [82] Verma, N., & Gupta, S. (2019). Assessment of LDPE degrading potential *Aspergillus* species isolated from municipal landfill sites of Agra. *SN Applied Sciences*, 1, 2019, pp. 1-10.
- [83] Chien, H. L., Tsai, Y. T., Tseng, W. S., Wu, J. A., Kuo, S. L., Chang, S. L., Huang, S. J., & Liu, C. T. "Biodegradation of PBSA Films by Elite *Aspergillus* Isolates and Farmland Soil". *Polymers*, vol 14, no 7, 2022, pp. 1320.
- [84] Dharshni, S., & Kanchana, M. (2021). "Microbial degradation of low-density polyethylene (ldpe) by fungus isolated from landfill soil". *Plant Archives*, vol 21, no 1, 2021, pp. 09725210
- [85] de Oliveira, T. A., Barbosa, R., Mesquita, A. B., Ferreira, J. H., de Carvalho, L. H., & Alves, T. S. "Fungal degradation of reprocessed PP/PBAT/thermoplastic starch blends." *Journal of Materials Research and Technology*, vol 9, no 2, 2020, pp. 2338-2349.
- [86] Antipova, T. V., Zhelifonova, V. P., Zaitsev, K. V., Nedorezova, P. M., Aladyshev, A. M., Klyamkina, A. N., ... & Kozlovsky, A. G. "Biodegradation of Poly-ε-caprolactones and Poly-l-lactides by Fungi." *Journal of*

- Polymers and the Environment*, vol 26, 2018, pp. 4350-4359
- [87] Lii, B., Wong, C., Al-Obaidi, J. R., Norasfaliza, R., Aazani, M., & Moritz, M. "Ability of endophytic fungi isolated from *Nepenthes ampullaria* to degrade polyurethane". *Malaysian Journal of Microbiology*, vol 13, no 3, 2017, pp. 172-179.
- [88] Oviedo-Anchundia, R., del Castillo, D. S., Naranjo-Morán, J., Francois, N., Alarcón, A., Villafuerte, J. S., & Barcos-Arias, M. "Analysis of the degradation of polyethylene, polystyrene and polyurethane mediated by three filamentous fungi isolated from Antarctica." *African Journal of Biotechnology*, vol 20, no 2, 2021, pp. 66-76.
- [89] Ren, G. C., Pang, A. M., Gao, Y., Wu, S. X., Ge, Z. Q., Zhang, T. F., ... & Gui, H. "Polyurethane-degrading fungi from soils contaminated with rocket propellant and their ability to decompose alkyne terminated polybutadiene with urethane". *Studies in Fungi*, vol 6, no 1, 2021, pp. 224-239.
- [90] Osman, M., Satti, S. M., Luqman, A., Hasan, F., Shah, Z., & Shah, A. A. "Degradation of polyester polyurethane by *Aspergillus* sp. strain S45 isolated from soil". *Journal of Polymers and the Environment*, vol 26, 2018, pp. 301-310.
- [91] Chaudhary, A. K., & Vijayakumar, R. P. "Studies on biological degradation of polystyrene by pure fungal culture"s. *Environment, Development and Sustainability*, vol 22, no 5, 2020, pp. 4495-4508.
- [92] Satti, S. M., Shah, Z., Luqman, A., Hasan, F., Osman, M., & Shah, A. A. "Biodegradation of Poly(3-hydroxybutyrate) and Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) by Newly Isolated *Penicillium oxalicum* SS2 in Soil Microcosms and Partial Characterization of Extracellular Depolymerase". *Current Microbiology*, vol 77, no 8, 2020, pp. 1622–1636.
- [93] Vivi, V. K., Martins-Franchetti, S. M., & Attili-Angelis, D. "Biodegradation of PCL and PVC: *Chaetomium globosum* (ATCC 16021) activity". *Folia Microbiologica*, vol 64, no 1, 2019, pp. 1–7.
- [94] Chaudhary, A. K., Chaitanya, K., Dalmia, R., & Vijayakumar, R. P. "Synergistic effect of UV, thermal, and chemical treatment on biological degradation of low-density polyethylene (LDPE) by *Thermomyces lanuginosus*." *Environmental Monitoring and Assessment*, vol 193, no 8, 2021, pp. 513.
- [95] Spina, F., Tummino, M. L., Poli, A., Prigione, V., Ilieva, V., Cocconcelli, P., Puglisi, E., Bracco, P., Zanetti, M., & Varese, G. C. "Low density polyethylene degradation by filamentous fungi". *Environmental pollution (Barking, Essex 1987)*, vol 274, 2021, pp. 116548.