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Potential application of fungal biosorption and/or bioaccumulation for the bioremediation of wastewater contamination: A review

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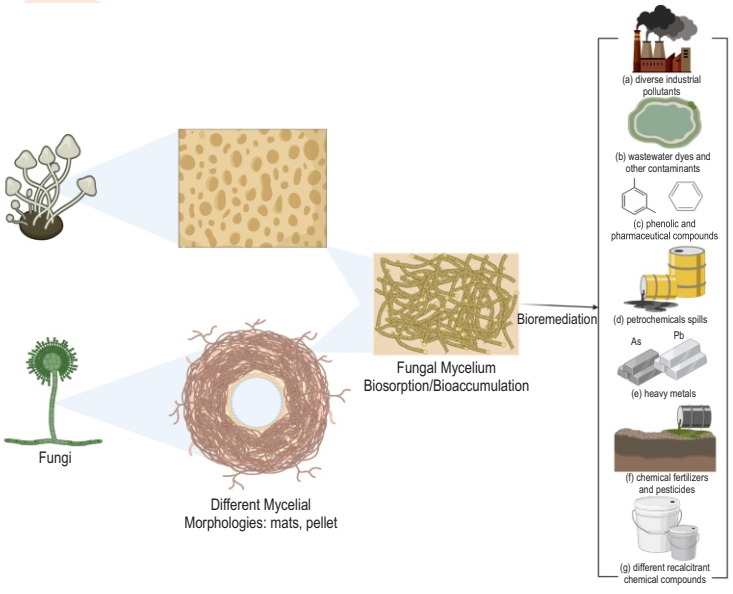
Abstract

The environment pollution or contamination is a serious problem, a great deal of research is being undertaken to combat contaminants such as xenobiotic and recalcitrant compounds, particularly heavy metals, dyes,phenolic compounds and other recalcitrant pollutants produced by a wide range of industrial activities. These compounds have an adverse impact on the environment, particularly when generated by industrial processes and then disposed off without adequate treatment. Mycoremediation is defined as the use of fungi for bioremediation, especially degradation or retention of contaminants. Biosorption and bioaccumulation are two of the mechanisms by which fungi remove contaminants through mycelium. In many cases, these processes involve metabolization and even mineralization of these contaminants, corresponding to a biological contaminant removal system with great potential for use in bioremediation processes.



The present review describes the unique characteristics of fungal mycelium that make it a biomaterial with potential applications in various fields of biotechnology, specifically evaluating its biosorption/bioaccumulation properties and potential application for the bioremediation of different water-borne contaminants. This review focus on the researches conducted on the bioremediation of inorganic and organic pollutants, the mechanisms involved in the process, and the main environmental factors affecting it. Moreover, kinetics and equilibrium modeling of the removal efficiency achieved via biosorption/bioaccumulation is analyzed in order to better understand these processes and overcome some of the technical barriers to their large-scale application in the mycoremediation of wastewater.

Key words: Bioaccumulation, Biosorption, Fungi, Mycoremediation, Xenobiotics

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Introduction

There is increasing public concern over persistent inorganic and organic toxic pollutants present in industrial and urban effluents. The potential of these compounds for bioaccumulation and toxicity in living organisms is associated with their persistence (Filote *et al.,* 2021; Igiri *et al.,* 2018). These compounds include heavy metals, polycyclic aromatic hydrocarbons (PAHs) and other petroleum-derived hydrocarbons, polychlorinated biphenyls, pesticides, pharmaceuticals, additives, and dyes (Top and Springael, 2003). Due to their complex structure, they are considered recalcitrant, as they are resistant to degradation via chemical, physical, biological, or microbiological methods, negatively affecting the environment when released without adequate treatment (Gbeddy *et al.,* 2020; Ncube *et al.,* 2020; Attallah *et al.,* 2019).

Fungi constitute a group of unicellular and multicellular organisms with a great number of industrial and environmental applications (Kour *et al.,* 2019; Musa *et al.,* 2018). The use of fungi to bioremediate contaminated environments, particularly wastewater, has many advantages over other types of treatments, especially in terms of efficiency, simplicity, flexibility of operation, cost-benefit results, and environmental friendliness (Legorreta-Castañeda *et al.,* 2020; Silva *et al.,* 2019; Ahuacizin-Pérez *et al.,* 2014). Biosorption using the viable or inactivated biomass of various fungal species has been explored as an important mechanism for the remediation of a large number of contaminants. Various filamentous fungi, including white rot fungi and yeasts, have been effectively used to reduce the levels of both organic and inorganic pollutants found in the wastewater produced by different industries, due to their high binding-capacity, high selectivity, and high degradation level and rate (Sharma *et al.,* 2023; Danouche *et al.,* 2021; Igiri *et al.,* 2018). Due to the efficiency of fungal biomass, either through biosorption or bioaccumulation processes, in eliminating different types of contaminants, these organisms are useful in the bioremediation of different environments contaminated by industrial pollutants (Gunyar and Uztan, 2021; Patel *et al.,* 2020; Rudakiya *et al.,* 2019).

Fungal mycelium a biomaterial with great potential: Mycelium is constituted by a mass of filaments known as hyphae, which ramify and form the mycelial lattice comprising the main structure of a fungus (Islam *et al.,* 2017). Mainly comprising natural polymers such as chitin, cellulose, and glucans and an external layer of proteins such as mannoproteins and hydrophobins, the cell wall of the hypha performs various physiological functions in the morphogenesis of fungi, simultaneously protecting the hyphae and providing the mycelium its mechanical force (Sánchez *et al.,* 2004; Téllez-Téllez *et al.,* 2003; Bartnicki-Garcia, 1968). Mycelium generally reproduces through formation of spores, either directly or in fruiting bodies, with the spores settling and germinating a specific location, then develop that hyphae elongate and branch, which is capable of capturing nutrients. Materials based on chitin-β-glucan complexes derived from the fruiting bodies or mycelial biomass cultivated on solid or liquid substrates have been used to replace petroleum-based products and have significant applications in the construction, textile, and packaging industries (Gandia *et al.,* 2021; Attias *et al.,* 2020; Appels *et al.,* 2019; Pelletier *et al.,* 2019). Mycelium can be defined as a biomaterial, a fibrous polymer whose composition and properties are closely related to fungal species, their growth conditions, and the nutritious substrates on which they develop (Yang *et al.,* 2021; Sánchez *et al.,* 2006). It has been suggested that mycelial layers, or lamellae, can be used as biological filters to eliminate chemical products and microorganisms from water and soil (Igiri *et al.,* 2018). In liquid medium, filamentous fungi grow as disperse mycelium or form visible granules or pellets that are visible as microspheres. Fungal pellets are a source of enzymes useful for the degradation of organic compounds (Téllez-Téllez *et al.,* 2008; Viniegra-González *et al.,* 2003; Díaz-Godínez *et al.,* 2001). Moreover, biosorption and/or bioaccumulation processes that occur via cell wall eliminate compounds, mainly due to the presence of varied functional groups capable of interacting with inorganic and organic contaminants via different chemical forces (Legorreta-Castañeda *et al.,* 2020; Khan *et al.,* 2019).

Biosorption and/or bioaccumulation: Microbial biosorption and microbial bioaccumulation are different processes, with particular aspects that should be identified in order to understand them. Biosorption refers to the ability of certain biomolecules or microbial biomass (either live or dead) to bond and concentrate the ions or other molecules present in aqueous solutions (Volesky, 2007). The basic principle of bioadsorption, which is a passive phenomenon carried out by dead biomass or certain molecules, relates to the "affinity" between the bio-adsorbent and the sorbate, corresponding to the biomass and the contaminant, respectively. The affinity process includes physical and chemical adsorption, ion exchange, complexation, chelation, and micro precipitation that occur mainly on the cell surface (Sadhasivam *et al.,* 2009). Biosorption, in aqueous solution, of different inorganic and organic pollutants depends on fungal cell wall components such as chitins, glucans, and mannans and functional groups such as amino, carboxyl, thiol, and phosphate groups. These elements are involved in stoichiometric relationships, physico-chemical interactions, and the binding of the pollutant to the cellular surface (Shourie and Vijayalakshmi, 2022; Sintakindi and Ankamwar, 2021; Zhu *et al.,* 2019).

Bioaccumulation is a more complex phenomenon than biosorption since it is based on active metabolic transport, which involves contaminating compounds passing through the membrane into the cell, where they accumulate and, in some cases, metabolize (Volesky, 2007). This process begins with biosorption, thereafter, the pollutants are transported into the cells mainly via energy-consuming active transport systems or facilitated trans-membrane transport (Shourie and Vijayalakshmi, 2022; Filote *et al.,* 2021) (Fig. 1). The main factors reported to affect pollutant-removal efficiency via biosorption are pH, temperature, contact time, pollutant properties, initial pollutant, and biomass concentration (Sintakindi and Ankamwar, 2021; Silva *et al.,* 2019). Diverse biological effects of heavy metal

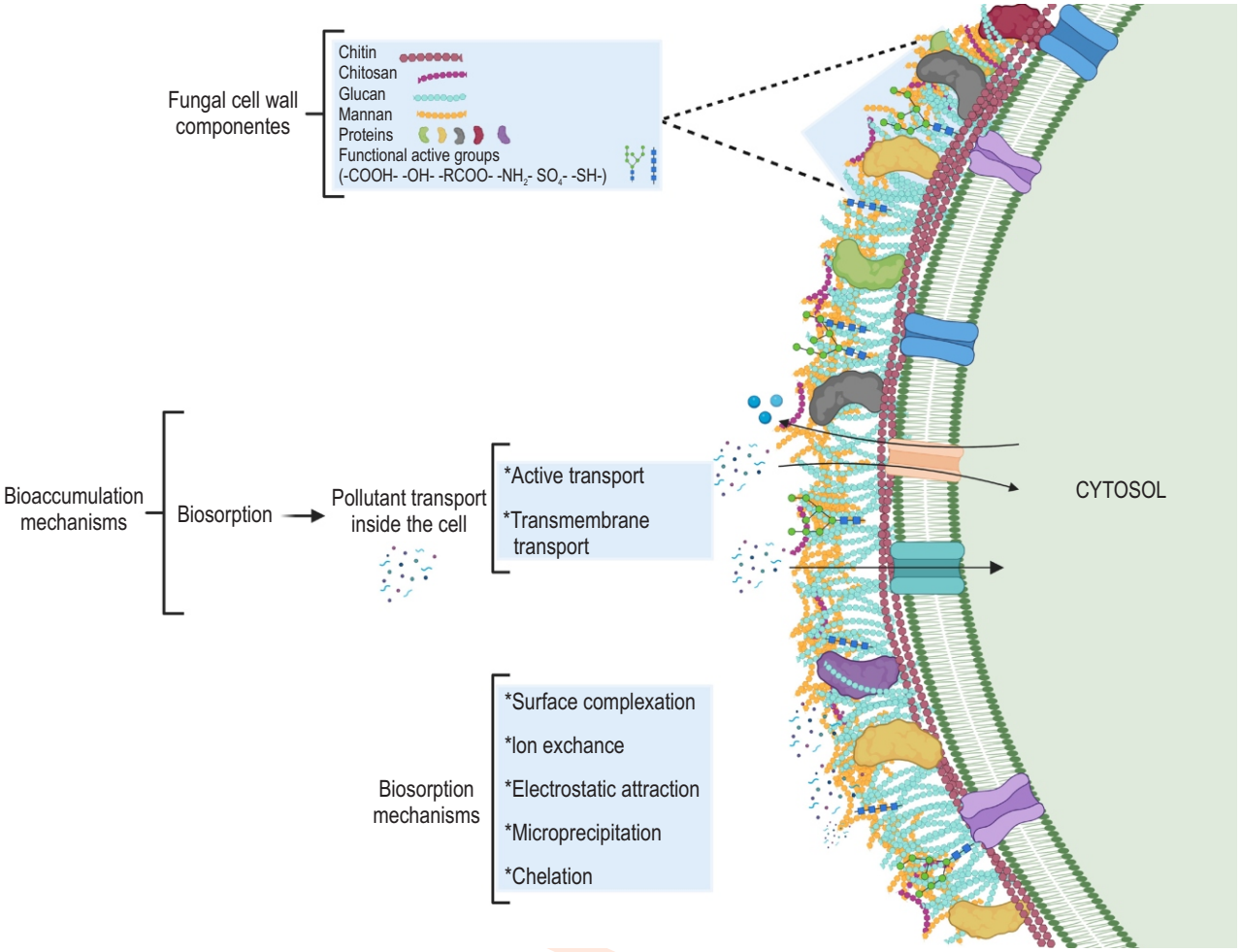

Fig. 1: Main biosorption and bioaccumulation mechanisms and principal fungal cell wall components involved in those processes (Adapted from Danouche *et al.,* 2021; Igiri *et al.,* 2018; Shourie and Vijayalakshmi, 2022).

exposure on microorganism have been reported. The effects of heavy metals depend on the specific speciation of metal and the model organism tested (Poljsak *et al.,* 2010). Factors related to the chemical nature, toxicity, initial concentration, availability, solubility, hydrophobicity/ hydrophily, and polar/nonpolar character of these compounds have contributed to the success of the biosorption and remediation of organic pollutants (Filote *et al.,* 2021; Sayara *et al.,* 2015).

Adsorption isotherms and kinetic models: In order to explain the biosorption mechanisms involved in the removal of both inorganic and organic pollutants, various kinetic and equilibrium models have been proposed. As the physico-chemical mechanisms involved in biosorption are complex, no simple theory of adsorption could adequately interpret experimental results (Wu and Yu, 2006). While evaluating the efficiency of the adsorption process, determining the adsorption equilibrium correlation is of great importance, which is achieved via the use of so-called adsorption isotherms, curves that explain the phenomenon of retention and/or release of a compound by the adsorbent material (Foo and Hameed, 2010). It is important to determine, at certain time intervals, the amount of contaminant compound adsorbed by fungal biomass at constant pH and temperature conditions, a measurement called the adsorption equilibrium, which determines the ratio of the amount of pollutant that has been adsorbed and the amount that has not. The adsorption equilibrium (q_e) can be determined via the expression $q_e = V(Ci - Ce)/W$, where V is the volume of the fluid containing the pollutant to be adsorbed, Ci and Ce are the respective initial and final concentrations (in equilibrium) of the pollutant, and W is the dry weight of the fungal biomass (Dhankhar and Hooda, 2011). The linear least squares method has been used to determine the parameters of the adsorption isotherms, but they show poor reproducibility, so non-linearized models are the better option (Dhankhar and Hooda, 2011). Although the mathematical modeling of the adsorption isotherms is obtained experimentally, many models are empirical trying to explain the experimental data with equations of two or three parameters and of a single

component, or multiple components. Some of the most used non-linearized models to obtain the adsorption isotherms are shown in Table 1 (Nomenclature. a_R, Redlich–Peterson isotherm constant; a_{RP}, Radke–Prausnitz isotherm model constant; a_S, Sips isotherm model constant; A_T, Tempkin isotherm equilibrium binding constant; b, Langmuir isotherm constant; b_T, Tempkin isotherm constant; C_e, equilibrium concentration; C_s, adsorbate monolayer saturation concentration; C_{BET}, BET adsorption isotherm relating to the energy of surface interaction; ε, Dubinin–Radushkevich isotherm constant; g, Redlich-Peterson isotherm exponent; k_{ad}, Dubinin-Radushkevich isotherm constant; K_F, Freundlich isotherm constant related to adsorption capacity; K_R, Redlich–Peterson isotherm constant; K_s, Sips isotherm model constant; n, adsorption intensity; q_e, amount of adsorbate in the adsorbent at equilibrium; q_s, theoretical isotherm saturation capacity; Q_0, maximum monolayer coverage capacities; r_R, Radke–Prausnitz isotherm model constant; R, universal gas constant; T, temperature; β_R, Radke–Prausnitz isotherm model exponent; β_s, Sips isotherm model exponent).

Sorption kinetics describes the time period for which the compound resides in the solid-solution interface, as well as providing information on the sorption mechanisms and pathways (Mohamed *et al.,* 2021). While several mathematical models describe sorption kinetics, the most commonly used are the pseudo-first-order model and the pseudo-second-order model. The pseudo-first-order equation is applicable during the initial stages of the sorption process, while the pseudo-second-order equation enables the description of almost all the kinetic data corresponding to the interactions between compounds and biomass (Dhankhar and Hooda, 2011). Among the mathematical models most commonly used to obtain the adsorption isotherms are those generated by Langmuir and Freundlich. These studies are based on the adsorption of lead by *Penicillium* sp. and *Cunninghamella elegans,* where the Langmuir-Freundlich model best described the experimental results (Ezzouhri *et al.,* 2010; Jadhav and Mahish, 2020). In another study, *Aspergillus versicolor* was used for removal of Pb^{2+} and Cu^{2+}, and the biosorption data obtained was explained by the Freundlich adsorption isotherm model and followed a pseudo-second order kinetics reaction (Gazem and Nazareth, 2012). Tsekova *et al.* (2007) reported adsorption of copper and cobalt by *Penicillium brevicompactum* cells, using the Langmuir and Freundlich isotherms. They observed that the adsorption of metals was a competitive process. *Cunninghamella elegans* mycelium was used for adsorption of three reactive azo dyes (Red, Black, and Orange II) present in the textile effluents, the Freundlich adsorption isotherm model showed the best fit (Ambrósio *et al.,* 2012). Sintakindi and Ankamwar (2021) carried out a bibliographical review of studies of fungal biomass used to remove colorants in solution. They concluded that the Langmuir and Freundlich adsorption isotherms were the best models for describing the maximum adsorption capacity of the dyes, while the kinetic studies conducted identified the reaction mechanism and pseudo-second-order kinetics, with predominantly chemical forces involved in the adsorption.

Applications of fungal-based biosorption and/or bioaccumulation for bioremediation: A large number of highly complex, toxic, and persistent xenobiotic and/or recalcitrant compounds generated by various human activities are present in the environment (Ijoma *et al.,* 2017). Examples of these activities include the agricultural use of chemical fertilizers and pesticides, different types of medications such as antibiotics, a great variety of food additives, and soaps, shampoos, and oils, among other products, in the personal care sector. Heavy metals, compounds such as PAHs, dyes, phenols, and many other recalcitrant compounds form part of the waste and/or effluent generated by the mining, petrochemical, food, and textile industries and often contaminate the soil and water bodies when they are not subject to adequate treatment prior to discharge (Yadav *et al.,* 2021; Noman *et al.,* 2019; Garzón-Zúñiga *et al.,* 2018; Rawat *et al.,* 2016). To date, numerous reports have been published on the effectiveness of fungi in removing different compounds via mycelial biosorption or biomineralization and biotransformation (Shourie and Vijayalakshmi, 2022; Bokade *et al.,* 2021; Ijoma *et al.,* 2017). Due to the presence of different functional groups in the cell wall, fungal biomass, either live or dead, has been observed to be an efficient bio-adsorbent of different contaminants (Legorreta-Castañeda *et al.,* 2020). Mycelium pellets present superior characteristics than mycelium itself in terms of bio-

Table 1: Some adsorption isotherm models

Model		Equation
Two parameter models	Langmuir	$q_e=Q_0bC_e/(1+bC_e)$
	Freundlich	$q_e=K_FC_e1/n$
	Tempkin	$q_e=(RT/b_T)LnA_TC_e$
	Dubin–Radushkevich	$q_e=(q_s)Exp(-k_{ad\varepsilon}2)$
Three parameter models	Redlich–Peterson	$q_e=K_RC_e/(1+a_RC_e^{\ g})$
	Sips	$q_e=K_sCe^{\beta s}/(1+a_sCe^{\beta s})$
	Radke-Prausnitz	$q_e=a_{RP}r_RC_e^{\ \beta R}/(a_{RP}+r_RC_e^{\ \beta R}-1)$
	BET	$q_e=q_sC_{BET}C_e/\{(C_s-C_e)[1+(C_{BET}-1)(C_e/C_s)]\}$

(Adapted from Foo and Hameed, 2010).

absorption of heavy metals, pesticides, dyes, and pharmaceuticals (Bokade *et al.,* 2021; Legorreta-Castañeda *et al.,* 2020). It is suggested that fungi are able to metabolize the compounds they have acquired via biosorption, in some cases even mineralizing them, in a process of bioconversion and biodegradation which has been explored in research on purifying the environmental matrices of various contaminants.

As mentioned previously, fungal biosorption does not involve metabolic energy or transport; however, such process can take place simultaneously in live biomasses. The remediation of wastewaters loaded with heavy metals is usually carried out by the following mechanisms: bioaccumulation, surface complexation, bioprecipitation, ion exchange, electrostatic interactions and cell surface adsorption (Priyadarshini *et al.,* 2021; Filote *et al.,* 2021; Ali, 2020). Biotransformation to less toxic metal species is achieved via reduction, oxidation, or alkylation, with metal complexation via proteins and chelation via ionic and covalent interactions (Priya *et al.,* 2022; Hansda *et al.,* 2016). Persistent organic pollutants can be removed by one or more mechanisms, including biosorption, bioaccumulation, cometabolism, biotransformation, biomineralization, and extracellular degradation. The majority of fungi (molds, yeasts and mushrooms) that have been subject of research are capable of metabolizing organic pollutants but not bioaccumulate them inside their cells (Filote *et al.,* 2021; Gunyar and Uztan, 2021). Biodegradation based on extracellular and/or intracellular enzymes is one of the most important mechanisms involved in the bioremediation of wastewater. The main extracellular enzymes that have proved to be effective in biodegradation are laccases and peroxidases (Shourie and Vijayalakshmi, 2022), although it depends on the solubility of the pollutant (Patel *et al.,* 2020; Silva *et al.,* 2019; Rudakiya *et al.,* 2019). The quantitative assessment of bioaccumulation is tedious as the process can involve chemical transport both into and out of the cell, passing through the cell membrane and some organelle membranes like vacuoles (Shourie and Vijayalakshmi, 2022; Ahmed *et al.,* 2017). The general mechanisms used by fungi to bioremediate different pollutant compounds are presented in Fig. 2.

Metal biosorption: Filamentous fungi are able to absorb heavy metals from both aqueous solutions and soil. Fungal biomass has been shown to carry out the sorption of Cu, Zn, Cd, Pb, Fe, Ni, Ag, Th, Ra, and U. This process depends on various parameters, such as pH, the concentration of metallic ions, and the type and quantity of biomass, while it can also be affected by the physical or chemical pretreatment of biomass, the presence of ligands, and, even, temperature. Basidiomycetes present a great advantage in

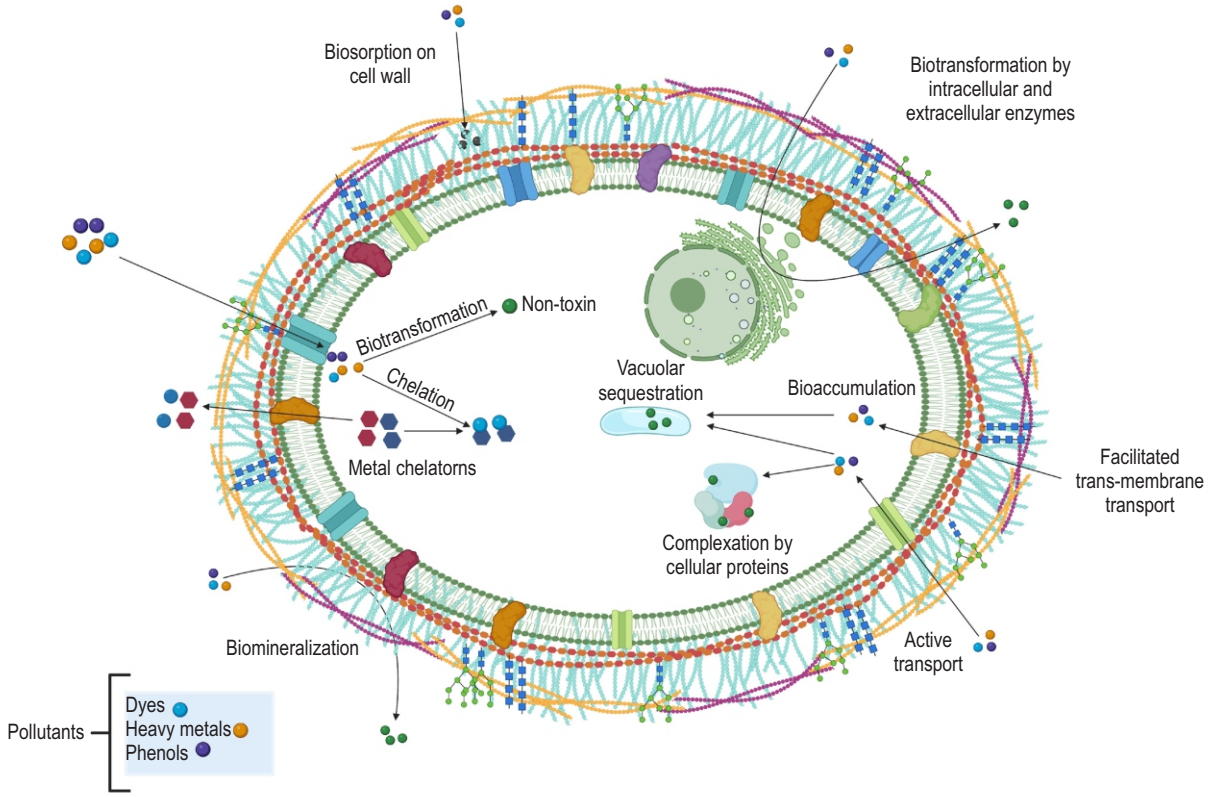

Fig. 2: Mycoremediation mechanisms for removal of inorganic and organic pollutants in aqueous solution (Adapted from Shourie and Vijayalakshmi, 2022).

the elimination of heavy metals, as they are very tolerant to different metals, a property related to the development of mechanisms of adaptation and metal accumulation (Xie *et al.,* 2017; Damodaran *et al.,* 2013). *Cunninghamella elegans* biomass used for the biosorption of lead ions reaching 80.72%, with a tolerance index of 92.3 in the presence of 50 mg l^{-1} lead nitrate (Jadhav and Mahish, 2020). Another study reported that *Coprinus atramentarius* was able to accumulate 76% Cd from 1 mg l^{-1} Cd solution (Xie *et al.,* 2017). Damodaran et al. (2013) reported that the fruiting body of *Galerina vittiformis* accumulated heavy metals (Pb(II) > Cd(II) > Cu(II) > Zn(II) > Cr(VI)) from 50 mg kg^{-1} of soil, suggesting that various cellular mechanisms are involved in the removal of heavy metals. Bala *et al.* (2020) evaluated isolates of *Aspergillus niger, Penicillium chrysogenum*, and *Rhizomucor* sp. for biosorption of Cd, Pb, and Zn metal. *Penicillium chrysogenum* achieved a higher level of Pb biosorption than *Aspergillus niger*.

Biosorption of dyes: Synthetic dyes are widely used in the textile, food, toy, and paper industries (Alsantali *et al.,* 2022; Benkhaya *et al.,* 2020). The complex chemical structures of these compounds make them highly persistent in the environment and resistant to both light and attack by microorganisms (Sen *et al.,* 2016). Most of the industrial effluents with dyes are discharged, without adequate treatment into the water bodies, or public drainage system (Noman *et al.,* 2019; Rawat *et al.,* 2016; Sen *et al.,* 2016). These effluents have a negative impact on the environment, due to varied raw materials, reagents, and production methods involved. Given that azo dyes are generally recalcitrant and present significant resistance to microbial degradation, their environmental impact is significant and, therefore, the implementation of methods for their correct treatment is of utmost importance (Nandi *et al.,* 2009).

To date, conventional wastewater treatments are generally inefficient in removing dyes and, moreover, involve high cost, the formation of dangerous sub-products, and high energy requirements (Arabaci and Usluoglu, 2014). Due to the foregoing, bioremediation through microorganisms is an environmentally-friendly, efficient and even, profitable alternative. The valuable potential of various fungi, bacteria, and algae species for the removal of dyes have been reported (Cao *et al.,* 2019; Martínez-Berra *et al.,* 2018; Grandes-Blanco *et al.,* 2013). Fungi present advantages over other organisms to this end, one of which is their oxidative mechanism, which avoids the formation of more toxic compounds, such as the anilines formed in bacteria-based dye reduction processes (Pointing, 2001). Fungi can be used to eliminate textile dyes via biotransformation, biodegradation, and/or adsorption by the biomass. Biotransformation of dye may involve a complete mineralization or formation of less toxic substances (Robinson *et al.,* 2001; Pointing and Vrijmoed, 2000; Deng *et al.,* 2008). Biosorption is a mechanism through which fungal biomass can efficiently adsorb and eliminate dyes from an aqueous solution and is related to the presence of functional groups on the surface of the cell wall of the fungus. This process plays an important role in the adsorption of cationic-type azo dyes (Noman *et al.,* 2019). White-rot fungi like *Phanerochaete chrysosporium*, *Bjerkandera* sp., *Trametes versicolor*, *Irpex lacteus* and *Pleurotus ostreatus* have been widely studied (Puchana-Rosero *et al.,* 2017; Toh *et al.,* 2003). The biomass of these organisms has been used as a bio-adsorbent and/or producer of enzymes that participate in biotransformation and biodegradation. Mycelium, applied either alone or in combination with other materials, can be used as a low-cost adsorbent that is effective for the elimination of dyes from aqueous solutions (Bayramoglu and Yilmaz, 2018; Przystaś *et al.,* 2018). Bayramoglu and Yilmaz (2018) used *Lentinus concinnus* biomass in polyvinyl alcohol/polyethylene oxide hydrogels to eliminate Reactive Yellow-86 dye from an aqueous solution. They reported that the carboxylate, hydroxyl, and amine groups participate in dye adsorption. Przystaś *et al.* (2018) reported the efficiency of immobilized biomass of *Pleurotus ostreatus*, *Gleophyllum odoratum*, and *Polyporus picipes* in decoloring Evans Blue and Brilliant Green (azo and triphenylmethanol dyes, respectively). Kaushik *et al*., (2014) used *Aspergillus lentulus* pellets, both untreated and subject to thermal treatment, to evaluate the level of biosorption of a textile dye (acid blue 120), with the untreated and treated pellets removing 55.0 and 56.7 mg g^{-1}, respectively. They demonstrated that the phosphate and $–CH_3$ groups play an important role in determining the biosorption capacity of pretreated fungal biomass. The mono azo dye Allura Red was bioasorbed from an aqueous solution using *Pycnoporus cinnabarinus*, *Pleurotus ostreatus* and *Trametes hirsuta* (Pecková *et al.,* 2021). Recently, Juárez-Hernández *et al.* (2021) reported the isolation from a textile industry effluent of an *Ammialatemarginata strain* with high capacity to decolorize azo, indigo, and anthraquinone dyes. Indigo and Remazol Brilliant Blue R dyes were the most susceptible, presenting decolorization percentages of up to 100% in both plate and submerged fermentation.

Biosorption of phenolic compounds and pharmaceuticals: The presence of phenolic compounds in effluents is common in the pharmaceutical, chemical, petrochemical, and pulp and paper industries, as well as in those industries which use solvents, paints, wood preservatives, or disinfection processes. These are the main sources of phenol contamination in groundwater reserves. These compounds not only harm the flora and fauna that come in contact with them, but they are also carcinogenic and due to their recalcitrant nature their harmful impact. Wastewater containing phenolic compounds require treatment prior to discharge. Biological methods, namely adsorption with activated carbon, extraction using solvents, chemical oxidation, and electrochemical treatments are the most common methods used for the removal of toxic compounds from wastewater (Legorreta-Castañeda *et al.,* 2020). Currently, bio-adsorbents are an ecological, effective, and low-cost option, with potential candidates for use as bio-adsorbents including fungi, algae, bacteria, and agricultural waste. The fungi *Pleurotus ostreatus, Phanerochaete chrysosporium, Lentinus edodes, Trametes versicolor*, and *Ganoderma lucidum* have been reported to be highly effective in eliminating aromatic chlorinated phenolic

compounds and polycyclic aromatic hydrocarbons (PAHs), present in water or soil (Rathankumar *et al.,* 2020; Košnář *et al.,* 2019; Nguyen *et al.,* 2014; Farkas *et al.,* 2013). One study explored the elimination of phenol and 2-chlorophenol from an aqueous solution using pellets, both live and heat-inactivated of *Funalia trogii*, finding that the efficiency of phenol elimination increased significantly in line with an increased quantity of biomass. The study concluded that the removal of phenols by means of live or heat-inactivated fungal pellets occurred via a process of physical adsorption (Bayramoglu *et al.,* 2009). Kumar *et al.* (2009) evaluated the capacity of dead *Trametes versicolor*, to eliminate phenol, 2-chlorophenol and 4-chlorophenol from water in experimental conditions, obtaining maximum adsorption results of 50, 86 and 112 mg g^{-1} for phenol, 2-chlorophenol and 4-chlorophenol, respectively. Kumar and Min (2011), used the dead mycelium of *Schizophyllum commune* to eliminate phenol, 2-chlorophenol and 4-chlorophenol from water under experimental conditions. Having evaluated the effect of pH, contact time, initial adsorbate concentration, and biosorbent dose, the authors found an adsorption capacity for the fungus of 120, 178, and 244 mg g^{-1} for phenol, 2-chlorophenol and 4-chlorophenol, respectively. Another study evaluated the use of non-viable pretreated cells of *Aspergillus niger, Rhizopus arrhizus*, and activated sludge to remove phenol (50 mg l^{-1}) from aqueous solutions in batch reactors. It was found that the initial pH, initial biosorbent concentration, and the adsorption time affected the adsorption rates (Kurnaz and Büyükgüngör, 2009).

Recently, *Aspergillus niger* biomass dust was proposed as a low-cost biosorbent for the removal of phenols (corresponding to vanillin, tannic acid, and the total amount of phenols in the pretreatment liquor) produced during the pretreatment of sugarcane bagasse with hot water. A 98% level of tannic acid removal was achieved via the use of biosorbent treated with NaOH, while the adsorption of vanillin was three times lower (Ribeiro *et al.,* 2021). The pharmaceutical industry is an enormous commercial sector subject to constantly-growing demand due to the fact that health is a human priority. It should be noted that the production and consumption of pharmaceutical products causes environmental contamination due to the fact that they contain harmful compounds of the type discussed in the present paper, with negative effects observed in organisms that come into contact with them, including human beings.

The use of fungi to treat wastewater generated by the pharmaceutical industry is a promising and environmentally-friendly technology. The presence of highly-adsorbent compounds such as chitin and chitosan in the cell wall of mycelium, fungi such as *Lentinus edodes, Agaricus bisporus, Trametes versicolor* and *Ganoderma lucidum* make them efficient in the removal of pharmaceutical compounds present in wastewater such as: paracetamol, estradiol, ibuprofen, ranitidine, and diclofenac (Menk *et al.,* 2019; Lucas *et al.,* 2016; Vasiliadou *et al.,* 2016). Jureczko and Przystaś (2021) tested the biosorption capacity of biomass of various fungi on two cytostatics (bleomycin and vincristine) in an aqueous solution, finding that live *Trametes versicolor* biomass presented the highest sorption capacity for bleomycin, while *Phyllotopsis nidulans* achieved the best results for vincristine. Lucas *et al.* (2016) evaluated the fungal sorption capacity on carbamazepine, diclofenac, iopromide and venlafaxine in wastewater. The sorption efficiency presented by the fungi for the contaminants ranged from 3 to 13% of the initial amounts used.

Biosorption of pesticides: Pesticides are widely use in agriculture for preventing and/or controlling crop pests, causing a negative impact on the environment. They are considered persistent pollutants and pollute soil, water, air, and agricultural products (Filote *et al.,* 2021; Huang *et al.,* 2018; Fenner *et al.,* 2013). Both their chemical structure and the environmental conditions under which they are applied define the transformation processes a given pesticide undergoes (Fenner *et al.,* 2013). Biotransformation is an effective process for degrading pesticides, enzymatic biotransformation is an effective process for degrading pesticides, the participation of different peroxidases, oxygenases and hydrolytic enzymes, has been reported for this process (Shourie and Vijayalakshmi, 2022). Fungi with potential use in the degradation of pesticides include *Aspergilusniger, Trametes versicolor, Lentinula edodes, Phanerochaetechrysosporium, Pleurotusostreatus* and species of the genera *Lecanicillium, Oxysporum, Phlebia, Thrichoderma, Mucor, Fusarium* and *Penicillium* (Shourie and Vijayalakshmi, 2022; Filote *et al.*, 2021; Parte *et al.*, 2017).

Recently, Beltrán-Flores *et al.* (2022) reported successful removal of pesticides diuron (3-(3,4-dichlorophenyl)-1,1-dimethylurea) and bentazon (3 -isopropyl-1H-2,1,3-benzothiadiazine-4 (3H)-one-2,2-dioxide) by *Trametes versicolor* immobilized on wood chips. Sorption and biodegradation of both pesticides present in an agricultural wastewater were observed. For bentazon degradation both laccase and cytochrome P450 enzymatic systems have been reported to be involved, and for diuron degradation only cytochrome P450 (Garcia-Vara *et al*., 2021; Hu *et al*., 2020). The fungal strains *Mucor racemosus* and *Mortierella* sp., isolated from soil contaminated with organochlorine pesticides have the capacity to degrade dieldrin and endosulfan, in liquid media containing 8.2 µM of each substance. *Mucor racemosus* degraded more than 90% of dieldrin over ten days of incubation at 25°C, while *Mortierella* sp. degraded over 70 and 50% of α and *β*-endosulfan, over 28 days of incubation at 25°C (Kataoka, 2018). Wu and Yu (2006) studied the biosorption of 2,4-dichlorophenol by non-living mycelial *Phanerochaete chrysosporium* pellets, finding a maximum sorption of 4.09 mg g^{-1} at pH 5.0. The capacity of fungi *Trichoderma harzianum* and *Metarhiziumanisopliae* to degrade the organophosphorus insecticides malathion profenofos and diazinon at different concentrations, incubation periods, and temperatures has been assed. The optimal conditions for organophosphorus insecticides degradation by *Trichoderma*. *Harizianum* and *Metarhiziumanisopliae* were 35°C and 30°C, respectively (Abd El-Ghany and Masmali, 2016).

Conclusions and perspectives: Both industrial development and implementation of new processes that generally involve the use of recalcitrant xenobiotic compounds pose a negative impact on the environment. Therefore, there is an urgent need for remediation methods that are environmentally friendly, economically feasible, and superior to the current methods used in terms of operational concerns, profitability, and effectiveness. Bioavailability, stabilization, and degradation of contaminants are the factors that direct and control the effective development of innovative methods for the remediation of different types of contaminants. Fungal biomass has been found to be an ecological biomaterial highly efficient in absorbing different types of contaminants and, thus, stabilizing them. Furthermore, it has been found to degrade or promote the bioavailability of contaminants for the action of other organisms, thereby, facilitating degradation. Understanding the biosorption mechanism and the modelling of such processes via the use of new strategies, as well as the design of system under realistic operating conditions, are the first steps to large-scale implementation of an effective biosorption-based bioremediation process.

Research conducted in the field of materials science and nanotechnology will contribute to the development of biomaterials, from the mycelium of fungal species, with properties that facilitate bioremediation. These innovations will, no doubt, be of significance to the large-scale establishment of ecological and efficient bioremediation methods. Finally, microorganisms that are potential candidates to be used in the development of new remediation methods will be those that guarantee an efficient removal of pollutants present in theindustrial effluents. As few studies have, to date, evaluated the effectiveness of fungal biomass in the remediation of industrial effluents, it is vitally important to evaluate these organisms under said conditions. It should be noted that contaminated sites and/or industrial effluent represent an opportunity for the isolation of organisms with great potential for bioremediation of persistent pollutants, thus contributing to the development of cleaner and cheaper technologies for the treatment of sites contaminated by industrial activities. It is clear that the industrial use of biological methods should be explored further to ensure the resolution of possible technical problems that may present in their development and implementation.

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