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REVIEW

Myco-remediation of synthetic dyes: a comprehensive review on contaminant alleviation mechanism, kinetic study and toxicity analysis

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Abstract

A strong economic foundation can be achieved by the growth of a number of businesses, including food, paper, clothes, leather, and textiles. However, because of improper waste management, industrialization and modernization have resulted in the massive disposal of water effluent laden with harmful substances like dyes and heavy metals, which has negatively impacted the ecosystem. A new green technology called myco-remediation has emerged to battle harmful toxins while promoting sustainable development effectively and economically. This review employed enzymatic degradation, biosorption, and their influencing parameters for optimization in order to highlight the invaluable potential of fungal bioremediation for dye degradation. Current perspectives on enzyme immobilization techniques and kinetic studies of dye removal have been reviewed, which can aid in the selection of quick and effective removal processes. This research offers new insight into a criterion that is often overlooked in favor of dye decolorization efficiency: the toxicity assessment of pure dye and post-process metabolites produced following myco-remediation. Our attention has been directed towards toxicity analysis at many levels, including genotoxicity, phytotoxicity, and zoo-toxicity. This is important to keep in mind when considering the extensive implications of myco-remediation for the recycling and reuse of industrial effluent. Enzyme engineering and omics technologies have been highlighted as potential future developments.

Keywords Kinetics study · Myco-remediation · Synthetic dyes · Toxicity analysis · Wastewater management

Abbreviations

BOD	Biochemical oxygen demand
C_t	Dye concentration at time t
C_0	Dye concentration at initial time
Ce	Dye concentration at equilibrium
COD	Chemical oxygen demand
GC–MS	Gas chromatography–Mass spectrometry
GDP	Gross domestic product
K_f	Freundlich isotherm constant
K_l	Langmuir isotherm constant
LC–MS	Liquid chromatography–Mass spectrometry
LMEs	Lignin modifying enzymes
mg/g	Milligram per gram
q_e	Biosorption capacity
q_m	Maximum adsorption
TDS	Total Dissolved Solids
TS	Total Solids
TSS	TotalSsuspended Solids
TU	Toxicity Unit
UNDP	United Nations Development Program
WRF	White Rot Fungi

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Introduction

Urban development and advancement in industrialization have played an important role in fulfilling human needs. Industries like textiles, leather, pharmaceuticals, and food are operated on a large scale to meet human requirements (Vikrant et al. 2018). In developing countries, the

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textile industry is notable in the economy by offering direct employment and therefore contributes to national and global economics by improving Gross Domestic Product (GDP), which is being considered as the economic snapshot of countries (Farhana et al. 2022). But on the backside, the polluted industrial effluent water with organic xenobiotic compounds is toxic to organisms living in water bodies and may also result in loss of biodiversity too (Sosa-Martínez et al. 2020). Therefore, there is an urge for development in a manner that covers or present necessities without disturbing nature and the future generations also can satisfy their requirements. The European Commission has announced the European Green Deal with the agenda of preserving our environment by providing protection to ecosystems and its residing biodiversity. It also emphasized reducing air, water, and soil pollution, along with improving waste management. The UNDP sustainable development goals also emphasize climate improvement which is deteriorating day by day.

Synthetic dyes are one of the major environmental pollutants which is recalcitrant in nature and is abundantly present in textile effluents as well as different industrial wastewater (Routoula and Patwardhan 2020). According to studies done in 2015 by Paraschiv et al., the textile industry is one of the major sources of water pollution; it is believed that they account for more than 20% of the water levels that have been recorded in Turkey, Indonesia, China, and regions of eastern Europe like Romania, and Bulgaria (Paraschiv et al. 2015). Wastewater management has been emphasized in recent years, as these compounds are detrimental to ecosystems and human health. It also shows longer persistence in water bodies and is not readily degraded.

Synthetic dyes have been categorized into different groups on the basis of presence of the chromophore and the nature of dye. The presence of an aromatic structure in the dye makes it difficult for biological degradation. In dye-containing effluents, when the dye is coupled with synthetic intermediates, it is responsible for generating aromatic compounds which are highly toxic and capable of causing mutations and showing a carcinogenic effect (Ito et al. 2016). The presence of dye is detectable at very low concentration in water and makes it visibly unpleasant. In addition, the photosynthetic activity of water is affected, and as a result, it influences the fauna and flora of the water bodies where the dye containing effluent is gathered. Such changes ultimately lead to ecological imbalance (Rahimi et al. 2016). For this reason, proper waste management has been emphasized as a direct contributor to sustainable development.

When it comes to treating effluents that include dyes, bioremediation has proven to be more favorable than traditional physicochemical techniques including oxidation, adsorption, membrane separation, flocculation, and ion exchange (Khatri et al. 2018; Long et al. 2017; Robinson et al. 2002; Wawrzkiewicz 2012). Utilization of natural and/or recombinant microbes to degrade dangerous compounds by microorganisms provides great flexibility in the design of experiments and easy operating conditions. It is perceived as environmentally safe because this technique is utilizing the natural metabolic capacity of microbes to conquer xenobiotic compounds into harmless compounds (e.g., CO_2 and water) through mineralization or biotransformation (Ghosh et al. 2017). Among biological agents, bacteria may face a substrate diffusion limitation in cells, while fungal cells do not suffer from this issue. White rot fungi (WRF) have been uncovered and named the most advantageous in the bioremediation of synthetic dyes by utilizing biodegradation and biosorption. Through biodegradation and biosorption, white rot fungi (WRF) have been proven to be the most helpful in the bioremediation of synthetic colours, which termed as Myco-remediation (Tortella et al. 2015). This approach is more sustainable compared to traditional remediation methods, which often involve the use of chemicals or mechanical interventions that can have negative environmental impacts. Mycoremediation can be a cost-effective solution for cleaning up contaminated sites (Kumar et al. 2021). Fungi are relatively inexpensive to cultivate and maintain, and their ability to thrive in diverse environmental conditions reduces the need for costly infrastructure or specialized equipment. Unlike some conventional remediation methods that can further disturb ecosystems or generate additional waste, mycoremediation typically has a minimal environmental footprint. It is also responsible for the decline in zoo toxicity and phytotoxicity of wastewater. According to best of our knowledge, previously published review article describing about myco-remediation of synthetic dye but not uncovering this study from the toxicity perspective. As emphasized previously that it is highly needed to study toxicity of wastewater at different trophic levels (Jureczko and Przystaś, 2019). The previously available review article more focused on the biodegradation. Apparently there is a scope for review article which highlight significance of biosorption as dye removal process. Hence, we would like to emphasize the potential of biosorption process for treatment of dye containing wastewater.

The goal of this study is to emphasize the advantages of several fungal species, particularly White Rot Fungi and their enzymes for the control of wastewater effluents containing dyes. Different immobilization techniques of fungi or enzymes are also emphasized as improvements in the stability of myco-remediation. It is essential to optimize the dye degradation procedure and achieve maximum dye

decolorization efficiency. Furthermore, the biodegradation mechanism of dye decolorization has been discussed, as it is essential to understand the metabolites being produced. Enzymes are important as they have a crucial role in the biodegradation of dyes, whereas the physical characteristics of fungi make it suitable for biosorption of dye. The study of the zootoxic, phytotoxic, and genotoxic effects of contaminated water containing dyes versus biologically treated water has been focused as a prime factor for the implementation of myco-remediation as a green wastewater treatment. In addition, omics technology and enzyme engineering are discussed in brief as a future prospect of bioremediation.

Synthetic dyes

History and classification of dye

Synthetic dyes and chemicals have been utilized in several industries as they have multiple uses, especially in the clothing, paper, and leather manufacturing industries as a coloring agent (Imran et al. 2019). Due to the industrial revolution and the constant requirement for new products, dyes have been manufactured by modification of the dye chromogen- an atom which is responsible for dye color (Hagan and Poulin 2021). The growth of the dye industry is strongly connected with the growth of the textile industry. During the period of 1930–1950, synthetic fibers such as polyacrylonitrile, nylon and polyester were introduced, and it created both the opportunity and new challenges for textile industries (Herbst et al., 2006).

Dyes can be grouped according to a number of factors, including their chemical makeup, intended use, and extraction method (Srinivasan et al. 2019). Based on their nature, dyes have been divided into two broad categories in Fig. 1; 1. Natural dyes and 2. Synthetic dyes. Based on their extraction from their natural sources such as plants and animals, natural dyes are classified. As in this review, we are mainly focused on synthetic dye removal techniques, so we will further discuss its classification. In the chemical classification, the synthetic dyes are classified according to the chemical group they possess. They are primarily classified as 1. Azo dyes 2. Anthraquinone dyes, second 3. Triphenylmethane dyes. Acidic dyes, basic dyes, sulfur dyes, reactive dyes, dispersion dyes, direct dyes, and vat dyes are the different categories of dyes based on how they are used (Benkhaya et al. 2020).

Adverse environmental effects of synthetic dyes

Any kind of industrial pollutants affect the lithosphere, hydrosphere, or biosphere of the earth and pose adverse effects on residing biodiversity (Treu and Falandysz 2017). It consecutively leads to health risks to the environment, animals, plants, and sometimes may result in death as well (Ahmad et al. 2023). At present, developed and developing countries are facing great difficulties in many ways of environmental pollution (e.g., less efficiency for the treatment of wastewater, industrial residuals, solid waste, and unhygienic portable water with non-degradable/xenobiotic compounds). The main contributors to pollution are crude mining, oil spills, polluted water, chemical fertilizers, pesticides, plastic garbage, sewage waters, sewage disposal, and toxic chemicals (Landrigan et al. 2020; Lopes et al. 2022; Naseem et al. 2023; Navaratna et al. 2010).

The industrial revolution is combined with research and development in products and their various categories; due to this, approximately 100,000 commercial dyes exist at the current time. They are produced on a large scale and around 7×10^5 tons of them are released into the natural water stream which is responsible for making the water polluted (Gayathiri et al. 2022). As a result of this advancement and research in the chemical sciences, synthetic dyes demonstrated great stability against chemical, physical, and photolytic agents. They have become more resistant to chemical or biological processes of breaking and/or degradation

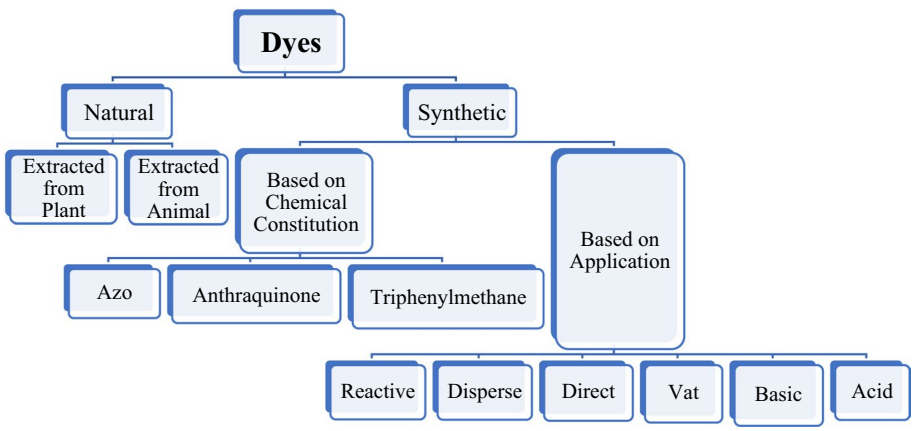

Fig. 1 Classification of dyes

(Julkapli et al. 2014). It becomes a serious environmental issue because the 0.6–0.8 g/L of dye concentration has been found in the mixture of wasted dye effluents (Beydilli et al. 1998; Vandevivere et al. 1998). The textile industry is the main contributor in these areas because it releases approximately 15% of the dye mixture into water bodies (Pearce et al. 2003); (Atiq et al. 2010; Singh et al. 2019). Chemical oxygen demand (COD), biological oxygen demand (BOD), total dissolved solids (TDS), total suspended solids (TSS), and total solids are all high in colored effluents discharged by different industries. Due to the change in their characteristics, this water becomes unfriendly to nature.

Additionally, pure dyes exhibit environmental toxicity, and some may even be able to cause cancer. As a result, its buildup in the ecosystem poses a serious threat to the environment and a health risk to all living things. The byproducts of their decomposition are frequently fatal, likely cancer-causing, and toxic to both plants and animals in many ways (Mendes et al., 2011). The large amount of colored waste in the water body causes acute toxic effects on aquatic animals, plants, and the entire aquatic ecosystem due to less light penetration and oxygen intake (Ahmad et al. 2020). The overall integrity of the biosphere becomes uncertain and imbalanced. Some of the most common azo dyes have been linked to a number of deadly illnesses, including splenic sarcoma, hepatocarcinoma, and human bladder cancer. Experimental animals have shown the nuclear abnormalities that result in chromosomal aberrations in mammalian cells (Heibati et al., 2015). It demands for the stringent application of environmental rules and regulations to control the discharge of colored water and raise awareness of the damaging effects of dyestuffs on the environment. The adverse consequences of toxic waste upon biodiversity becomes an attractive topic for researchers, and it is indicated by increased number of research publication in the field of biodegradation of dyes in the nearest past (Kunjadia et al. 2016).

Myco-remediation: mechanism of dye removal and effecting parameters

Fungi are widely distributed and can be found in nearly every kind of ecosystem, including freshwater, marine, desert, tropical rain forest, and deep-sea sediment environments (Vargas-Gastélum and Riquelme 2020). The ability of different fungal species to metabolize or digest different dangerous or persistent compounds is a characteristic that sets them apart from one another on a biochemical, physiological, and metabolic level. One of the best methods to clear the contaminated soil and water can be mycoremediation. The hazardous compounds are removed from the polluted medium both in-situ and ex-situ using live or dead fungus. The natural role of fungi as a decomposer makes them suitable as a natural degrader of various organic pollutants (Routoula and Patwardhan 2020)**.** The basic mechanism underlying dye decolorization is biodegradation, biosorption, and bioaccumulation which is further discussed in the detail. Microbes can effectively promote environmental rejuvenation by utilizing their natural metabolic capabilities through oxidizing, transforming, or immobilizing pollutants and contaminants. In other words, it is a cooperative and applicable phenomenon that includes processes that use biological systems to clean up or restore contaminated sites (Dubey et al. 2011; Rawat et al. 2011) and decrease contamination levels to less toxic, undetectable, or acceptable levels (Chaney et al. 1997).

Biodegradation

Different kinds of fungi have their own special mechanism for dye degradation. A fungal group like white-rot fungi belonging to family basidiomycetes, is the major group responsible for sufficient dye decolorization and degradation. In the group WRF, *Trametes versicolor*, *Pleurotus ostreatus, Schizophyllum commune*, *Pleurotus sapidus*, and *Pleurotus florida* were experimentally checked for degradative enzyme production such as ligninolytic enzyme activity and how it is involved in degradation. The process of removing dyes by fungi begins with adsorption onto the hyphae and continues when extracellular enzymes within the hyphae of the fungus break the chemical bonds holding the dyes together. Still, the underlying mechanism of myco-remediation is less well known. White-Rot Fungus has unique extracellular enzyme machinery which produces laccase, phenol oxidase, lignin peroxidase, Mn-dependent and Mn-independent enzymes which can naturally degrade highly stable or complicated structures (Zhuo and Fan 2021). Ligninolytic enzymes are the most important enzymes for the dye degradation activity of dyes. The main degradative enzymes, such as laccase and oxidoreductase, are the main enzymes produced by WRF. It produces intracellular and extracellular degradative enzymes that have low specificity, and using this phenomenon degradation of various dyes, toxic chemicals, and wastewater treatment can be carried out. The simple key to Myco-remediation involves determination of specific fungal species for the removal of specific pollutants

and understanding the mechanism. Different innovations in the design of various bioreactors and their management of dye-laden fungal biomass have been implemented in various sectors of industry (Kulshreshtha et al. 2014).

There are many methods and techniques invented in biotechnology and the immobilization of biomass to enhance enzymatic activity, but the immobilization of enzymes is one of the majorly used techniques for performing enzymatic activity in different ways. The basic meaning of immobilization is the combining the catalysts with an insoluble support matrix or carries which hold whole cell or isolated enzyme in a proper geometric position (Chatha et al. 2017). Many improvements have been made for easy recovery from a complex reaction mixture and convenient handling. It provides stable catalysts for practical work and implementation. Immobilization postulates great thermal stability and better resistance to enzyme denaturation as well aggregation (Bilal et al. 2017). For the immobilization of enzymes for diverse uses, several methods and procedures have been developed. Industries also use a variety of methods and tactics. The fundamental techniques and tactics for immobilizing enzymes are shown in Table 1.

Physical adsorption is the simplest and most quick reversible immobilization method among all, which can perform under mild conditions (Górecka and Jastrzębska 2011). By using forces like ionic interactions, van der Waals interactions and hydrogen-bond enzymes are physically absorbed or connected to the carrier surface. It is one of the lowest cost and simplest methods. But it has its own disadvantages, as adsorption has very poor stability of the absorbed enzymes (Hassan et al. 2019). Additionally, the formation of weak bonds between the enzyme and the carrier or support makes denaturation of enzymes conceivable.

In the second choice, covalent bonding is a mostly used enzyme immobilization technique for dye degradation. Specifically, it has its own advantages for wastewater remediation. It includes the covalent bonds establishment linking support material with functional groups of enzymes, like tyrosine, amino, hydroxyl groups. This method facilitates robust bonding between the enzyme and the carrier, which also provides elevated resistance to extreme operating conditions. As well as preventing permitted applications for batch and continuous operations, it also stops enzyme desorption and leakage (Minussi et al. 2002). However, even this approach has drawbacks: During the immobilization reaction, it leads to the alteration and destruction of the active conformation of the enzyme, which causes the first loss of enzymatic activity (Anjaneyulu et al. 2005).

Entrapment is a better option than immobilization. It is a method of irreversible immobilization in which the enzymes are physically restrained inside a cavity or porous matrix support, permitting the passage of substrate and products while retaining the enzyme. Gelatin, polysaccharides, and polymer are just a few of the supporting matrixes that are employed for it. It can achieve strong resistance to inactivation thanks to its supporting matrix's considerable enrichment in thermal and harsh stability (Torres-Farradá et al.

Table 1 Illustration of immobilization techniques for dye removal using myco-remediation

Immobilization techniques	Methods	Fungi	Enzyme	Dye	References
Covalent bonding	Diazoation, peptide bond, polyfunctional reagents	*Trametes versicolor, Trametes pubescens*	Laccase, peroxidase	Sodium fluorescein violet P4RN, sodium fluorescein golden yellow, sodium fluorescein Black BR, sodium fluorescein Blue	(Bilal et al. 2017)
Entrapment	Inclusion in fibers, Inclusion in the Gels, inclusion in microcapsules	*Coriolopsis Gallica, Trametes versicolor*	Laccase, peroxidase	Remazol brilliant blue R, laser dyes, rose bengal 5, brilliant blue Remazol brilliant blue	(Datta et al. 2013)
Encapsulation	Membrane based	Novozyme, *Trichoderma harzianum*	Peroxidase	AR	(Lu et al. 2007)
Adsorption	Static, dynamic batch, reactor loading, electrode position	*Trametes versicolor*	Laccase, peroxidase	Acid orange 7, acid blue 74, reactive red 2, reactive black 5	(Ramírez-Montoya et al. 2015)
Cross-linking	Copolymerization	*Trametes versicolor*	Laccase, Peroxidase	S.F Violet P4RN, S.F. golden-yellow CRL, S.F. black BR, S.F. Turq blue	(Bilal et al. 2017)

Table 2 Advantages & disadvantages of enzyme immobilization techniques

Advantage	Disadvantage
Enhanced level of strength and stability	Expensive
Increased level of reusability, reactivity and efficasy	Complex process, chances of failure
Improved level of product stability	Limited implementation
High enzyme substrate ratio	Support/carrier related limitations
Enhanced level of continuous operation	Inactivation caused by heat generated in the system
Less chances of contamination	Cross-linker requirement issues

2019). This is conceivable because enzymes that have been immobilized are shielded from denaturation in hostile environments. Additionally, there is some indication that the peroxidase enzyme may be trapped, enabling enzymatic reusability. Additionally, because of the enzyme's high decolorization effectiveness, it can be safeguarded and utilized repeatedly. The state of immobility also has benefits and drawbacks. After immobilization, enzyme catalytic activity efficiency, biological stability, and the capacity to carry out enzymatic activity in an adverse environment are all boosted. Table 2 lists the benefits and drawbacks of immobilizing enzymes.

Biosorption

The term "sorption" describes the process of either adsorption or absorption. The process by which a substance from one condition is incorporated into another (such as when liquids are absorbed by solids or gases are absorbed by liquids), is known as absorption. On the other hand, adsorption is the process by which ions and molecules physically cling to or connect with the surface of another molecule. Activated carbon is a common sorbent used in commercial sorption systems to remove dyes from wastewater due to its high adsorption capacity. However, because of its exorbitant cost, its general use is limited (Asgher 2012). Many strategies have been researched recently in an effort to create more affordable and efficient adsorbents. Using inactive and dead biomass, biosorption has been shown to be an efficient technique for removing dye molecules from diluted aqueous solutions. The morphological advantage of the fungal mycelium may prove to be quite beneficial in the remediation of dyes. A greater surface area due to the hyphae structure causes various contaminants to be absorbed or absorbed onto it. The sorption process on WRF biomass can be used to remove environmental contaminants that are hard to biodegrade since it is a metabolism-independent method of pollutant removal. Sorbents have been shown to be superior to other treatment methods in terms of their insensitivity to dangerous contaminants, ease of use, flexibility, and simplicity of design. Most importantly, the sorption process does not result in the production of dangerous compounds (Jureczko and Przystaś, 2021).

Different variations in bio-sorbent preparation

When synthetic dyes are found in industrial wastewater, they could be removed by living or dead biomass of fungi which act as a biosorbent. Macro fungal biomass is a perfect biosorbent since it is readily available and relatively inexpensive to generate. In dye removal, the whole live mycelium can be utilized (Iqbal and Saeed, 2007; Wang et al. 2015), as well as many researchers tried dried and powered mycelium (Kang et al. 2018; Puchana-Rosero et al. 2017). It is reported that autoclaved or dead mycelium has altered structure and functional groups present on the active site, which is responsible for different biosorption capacities of live and dead mycelium. When *Pleurotus ostreatus* strain (BWPH) was utilized for removal of Brilliant Green dye, the dead autoclaved biomass was able to remove less Brilliant green dye ($48.85 \pm 8.25\%$) compared to live mycelium under shaking condition ($95.00 \pm 0.27\%$) (Przystas et al. 2012). Similar results were obtained by Peckova et.al. (2021) for the removal of monoazo dye Allura Red AC by different WRF. They found that the dead biomass of *P.ostreatus* modified by heat was the most suitable biosorbent (118.3 ± 9.9 mg/g) (Legerská and Horník, 2021). Different dye removal capacities have been seen as a result of the interaction between the functional group of the dye and the carboxyl lipid group found in the cell wall of fungus.

Taking into account the previously mentioned data, employing living biomass as a biosorbent would offer a significant advantage in that it would be able to remove a larger quantity of contaminants. However, when using any kind of biomass, there are additional benefits and drawbacks to take into account. The majority of applications center on the use

of dead biomass because it avoids toxicity-related issues, requires no maintenance, can be stored for extended periods of time without losing effectiveness, is more feasible to regenerate, and can be used to address a wider range of environmental variables. Furthermore, this biomass can be processed and chopped into the right size of particles. Though dead biomass has all these benefits, using living biomass can also be beneficial because, as previously mentioned, the cells are metabolically active. This allows the pollutants to enter the cell and increase process efficiency because bioaccumulation aids in the initial biosorption process (Santaeufemia et al. 2016). In this scenario, the pollutant would bind to the cell surface in a first stage that would be independent of metabolism (biosorption in the strict sense) and then travel through the cell membrane to the interior of the cell in a second step that would be reliant on metabolism. It is important to consider that certain contaminants may potentially penetrate the membrane through passive diffusion at this point (Torres 2020).

Till date different organic, inorganic or biowaste support have been tested for immobilization of biomass (Naseem et al. 2023). These are relatively inexpensive support or left over products or waste generated from different industrial operations, agriculture waste etc. The researchers chose sugarcane baggase (Crespão et al. 2020), loofa sponge (Iqbal and Saeed, 2007), nylon sponge and sunflower seeds (Enayatizamir et al. 2011). Numerous studies have been done so far to examine the biosorbent qe's ability to remove dyes (mg/g). It indicates the capacity of dye absorption in milligram per gram of dry biosorbent. Biosorption can serve for dual purpose of utilization of waste for treatment of wastewater and contribute as a sustainable technology for wastewater treatment.

Kinetic study

As the study of decolorization rate and enzyme assay are important for evaluation of biodegradation mechanism of myco-remediation, likewise, the adsorption isotherm model and kinetics study will provide insight about the efficiency, mechanism and nature of biosorption reaction (Anjaneyulu et al. 2005). The rate of solute adsorption and the duration of the adsorbates' residence at the solid–liquid interface are both described by adsorption kinetics. Adsorption isotherms are crucial for predicting how the adsorbent and adsorbate interact as well as the adsorbent's ideal adsorption capacity (Naraian et al. 2018). Adsorption kinetics were studied for pseudo first order, pseudo second order, Elovich, Bhattacharya and Venkobachar, and Natarajan and Khalaf on the presumption that the process exhibits heterogeneous reaction behavior at the solid–liquid interface. In order to calculate the adsorption capacity of the adsorbent, rate constant, rate of adsorption, and intraparticle diffusion, a straight-line adsorption kinetics equation is presented. The calculated correlation coefficient value is used to calculate the adsorption. The adsorption isotherm models such as Langmuir and Freundlich models exist to analyze the pollutant removal mechanism. The Langmuir model suggests that the dye is removed by adsorption on the outer layer (monolayer adsorption), whereas the Freundlich model suggests multilayer adsorption of dye onto the fungal mycelium. When the biomass is autoclaved, it changes its properties which have an influence on dye removal. The rate-removal kinetics is also studied by many authors. It is presented in Table 3. It is observed that, but only up to a particular concentration, the dye sorption capacity increases as the original dye concentration rises. The dye uptake rate is then reduced after that point. The following might be used to calculate the biomass's capacity for biosorption qe (mg/g):

$$q_e = \frac{C_0 - C_t}{m} \times V \quad \text{(Chakraborty et al. 2013)} \tag{1}$$

where V (L) represents the volume of the solution, m (g) means the weight of the wet biomass, and qe denotes the biosorption capacity. C_0 and Ct (mg/L) reflect the dye concentrations in the solution at start and at time t, respectively.

The Langmuir (Eq. 2) and Freundlich (Eq. 3) model could be utilized for isotherm studies with the help of the equations given below.

$$\frac{1}{q_e} = \frac{1}{q_m k_l C_e} + \frac{1}{q_m} \quad \text{(Nandi et al. 2009)} \tag{2}$$

$$\log q_e = \log kf + \frac{1}{n} \log Ce \tag{3}$$

where Ce (mg/L) is the dye concentration at equilibrium and qe and qm are the biosorption capacity and adsorption maxima, respectively, and kf and kl are used as the Freundlich and Langmuir isotherm constants.

Table 3 Dye biosorption capacity of fungi and adsorption isotherm model

Fungi	Dye, concentration (mg/ L), pH, temperature (°C)	Biosorbent Form	Qmax (mg/g) capacity, time to reach equilibrium	Adsorption isotherm model	References
Phanerochaete chrysosporium	Remazol Brilliant Blue R, 10–500, 2, 30	Mycelium immobilized on Loofa sponge	101.06 ± 2.52, 40 min	Langmuir model Second order Kinetic model	(Iqbal & Saeed, 2007)
		Free Fungal Biomass	85.21 ± 2.98, 60 min	Langmuir model Second order Kinetic model	
		Only Loofa Sponge	5.84 ± 0.20	–	
Aspergillus sp. TS-A CGMCC 12,964	Mordant Yellow 1, 50, 3, 30	Powdered mycelia	9.1912, 10 min	Langmuir model Pseudo Second order Kinetic model	(Kang et al. 2018)
Pleurotus ostreatus	Red 4B, 50, 2, 25	Colonized sugarcane bagasse with fungi	10.63, 260 min	Freundlich model Pseudo Second order Kinetic model	(Crespão et al. 2020)
		Non-colonized by mycelium sugarcane bagasse	37.13, 260 min	Langmuir model at lower dye concentrations and Freundlich model at higher dye concentrations Pseudo Second order Kinetic model	
Haematonectria. Haematococca BwIII43	Alizarin blue black B 3, 7, 28	Living Biomass	247.47, 7 days	Freundlich model –	(Rybczyńska-Tkaczyk & Korniłłowicz-Kowalska 2016)
Trametes sp. SC-10	Acid Blue 161 100, 2, 30	Autoclaved and dried powdered biomass	221.6, 360 min	Langmuir model Avrami fractional-order model	(Puchana-Rosero et al. 2017)
Penicillium janthinellum sp. strain (P1)	Congo Red 400, 5, 30	ZJU-BS-P1 live mycelium pellets	344.83, 24 h	Langmuir model Pseudo Second order Kinetic model	(Wang et al. 2015)
Mucor circinelloides	Congo Red 300	Wet biomass	169.49, 60 min	Langmuir model –	(Azin & Moghimi 2018)
Thamnidium elegans	Reactive red 198 (RR198) 100	dried (60 °C) powdered biomass-batch system	234.24, 40 min	Langmuir model	(Akar et al. 2013)
		dried (60 °C) powdered biomass- column system	221.45	Pseudo second order kinetic model	

Effectiveness of process parameters for dye removal

There are several physicochemical variables like pH, temperature, agitation speed, initial dye concentration, effect of carbon sources, nitrogen source, C:N ratio, and live or dead biomass, which are being studied for the optimization of the dye degradation process using fungi (Fiaz et al. 2020). We have summarized the data on physicochemical parameters, percentage of decolorization, enzymes involved in the process, mechanisms involved, and metabolites produced in Table 4. The fungal strains that exhibit a higher percentage of decolorization in a shorter amount of time have been chosen for the studies. According to the review, fungi from several groups, including Ascomycota and Basidiomycota, are effective at producing enzymes that modify lignin and can decolorize dye by at least 70% to more than 90%. The decolorization of the dye is significantly influenced by the

Table 4 Details of Myco-remediation of dyes using fungal species, Effecting Factors, Mechanism

Fungal species	Dye	Factors-dye conc. (mg/L) time (h), pH, temp. (°C)	Decolor-ization (%)	Enzymes involved	Mechanism	References
Aspergillus niger	Brilliant green	10, 72, 5, 35	99.27	Lipase	Bio adsorption	(Kumar et al. 2012)
Aspergillus flavus SA2 192	Acid Red 151 OII	20, 192, 5.6, 30	97.70/55.68	Peroxidase, protease	Biosorption, Breakage of Azo-Bonds	(Ali et al. 2010)
Aspergillus foetidus	Remazol Brown, Remazol Red	50, 48, 7.5–8.5, 30	99–95	peroxidase, protease	Bio-absorption, Breakage of Dye Bonds	(Sumathi and Manju 2000)
Penicillium sp.	Acid Red 151 OII	20, 192, 5.6, 30	97.70	Lipases, proteolytic	Bio absorption	(Ali et al. 2010)
Penicillium oxalicum	Rhodamine B	100, 5, 7, 40	90	lipases, proteolytic	Bio-absorption	Das 2006
Penicillium ochrochloron MTCC 517	Cotton Blue	50, 2.5, 6.5, 25	93	Lipases, proteolytic	Asymmetric cleavage	Shedbalkr 2008
Curvularia clavata NZ2	Congo Red, Reactive Black 5, Acid Orange 7	100, 24, 5, ambient temperature	88–92	Laccase, MnP, Xylanase	Reduction of the azo bond	Neoh, 2015
Schizophyllum commune	Acid Orange 7, Acid Red 8, Reactive Black 5	100, 120, 2, 30	12.3/27/40.7	Laccase, Xylanase, endoglucanase	Biosorption, Cleavage of Dye Bonds	(Renganathan et al. 2006)
Rhizopus oryzae	Reactive black	100, 5, 7, 40	90	Lipase, Amylase, Protease, Cellulase	Biosorption	Das 2006
Rhizopus arrhizus	Germazol Torquoise Blue-G	100, 24, 2, 25	85.9	Hemicellulase	Biosorption	Aksu 2006
	Gryfalan, Black RL	500, 24, 1, 35	666.7 mg/g	Phytase	Biosorption	Aksu 2008
	Remazo l brilliant blue	800, 24, 2, 35	86.9	Tannase, Pectinase	Biosorption	Aksu 2000
Rhizopus nigricans	Reactive Green, Reactive Blue 3	2950, 1, 6	86 83	–	Ion exchange	Kumari 2007

Table 4 (continued)

Fungal species	Dye	Factors-dye conc. (mg/L) time (h), pH, temp. (°C)	Decolor-ization (%)	Enzymes involved	Mechanism	References
Neurospora crassa	Acid Red 57	100, 0.67, 1, 20	98.78	Exocellular protease	Biosorption	Akar 2006
Funalia trogii	Reactive Blue 19, Reactive Blue 49, Anionic Violet V43	100, 8, 4.5, 28	96.3 100 96.2	Laccase	Reduction of azo bonds	Park 2007
Cerrena sp.	Malachite green	110, 2.87, 6, 25	91.6	Laccase	Reduction of azo bonds and breakage	Hassan 2015
Thermomucor indicae-seudaticae	A mixture of Azure B, CR, Trypan blue, and Ramazol brilliant blue R	1000, 24, 6.0, 55	79.28	Cellulase	Biosorption, Breakage of Azo bonds	Taha 2014

pH of the culture media. The effectiveness of cationic or anionic dye gets affected based on the interaction between the charge of the dye and net charge on the fungal cell wall, depending on pH of the medium (Singh 2006). The incubation temperature of the fungi is also important to manage. Specifically, fungi have their own temperature range where it grows well and perform enzymatic activities at its best. The optimal temperature for *Pleurotus ostreatus* is in the range of 22–30 °C where the fungal morphology is intact and suitable for dye decolorization. Similarly, a difference in decolorization efficiency is observed when the fungus is grown in static conditions or on shaking condition. The speed of rotation has been tried in the range of 0–200 rpm, which has an influence on the mechanism of dye degradation. The structure and concentration of dye were the most influencing factors. Five structurally different dyes gave different decolorization percentages when tested for four initial dye concentrations, it is usually observed that at lower dye concentration and less dye with less complex structure, it is easier to degrade compared to a dye having high molecular weight and complex structure (Rajhans et al. 2021; Upadhyay et al. 2023).

As enzymes like lipase and peroxidases act on the dye molecule, it results into different metabolites that may be having less complex structure than the pure dye. The presence of metabolites produced by the degradation of Brilliant Green dye was detected by performing a wavelength scan from 200 to 800 nm. Before degradation, the maximum absorbance was observed at 625.8 nm, but after degradation, the absorption peak was detected around 261.3 nm, which confirms the formation of intermediated by aerobic decolorization of Brilliant Green (Kumar et al. 2012). Different analytical techniques such as LC–MS and GC–MS have been utilized for the detection of metabolites.

Likewise, the enzymatic dye degradation mechanism and the biosorption procedure are also subjective to change by different parameters, for example: initial dye concentration, pH, temperature, biomass dosage and ionic concentration. Congo red, a dye from the azo group, was chosen as the model dye for the examination of the impact of pH, and the pH range was 3.0 to 10.0. The results showed that when the pH rose from 3.0 to 5.0, the biosorption capacity increased, reaching its maximum capacity (98.49%) at pH 5.0. While further increase in pH was not proven to be beneficial for improving biosorption capacity. As was already established, the fungal cell wall contains a variety of functional groups, including carboxyl, amino, and phosphate. Because NH_4^+ functional groups on the surface of biosorbents may absorb H^+ ions, the active sites can become positively charged when the pH of the medium is tuned to be acidic. As a result, there is an increase in the electrostatic attraction between the positively charged bio-sorbent and the negatively charged Congo red ions. Additionally, it was discovered that mycelial

activity is affected by pH variations between 3.0 and 5.0. Improved dye removal efficiency and enhanced mycelial activity may be associated. When the pH is basic, there are more negatively charged active sites on the biosorbent surface, which is what causes the biosorbent to repel negatively charged dyes electrostatically (Sivaraj et al. 2001; Wang et al. 2015).

Another parameter is temperature, which affects biosorption and helps to determine the type of sorption process, like chemisorption or physisorption, depending on the exothermic or endothermic reaction type. The improvement in dye removal capability was also noted when the trial temperature was raised from 25 °C to 75 °C. The dye tested had a starting concentration of 1000 mg/L. As a consequence, at temperatures of 25 °C, 50 °C, and 75 °C, respectively, the dye removal efficiency was reported to be 73.8%, 89.9%, and 94.6%. The adsorption process is therefore recognized to be heat sensitive in nature and it is obvious of chemisorption in endothermic reactions where a progression is predicted in terms of dye removal efficiency as a result of raising the experimental temperature. The amount of 31,634 kJ/mol enthalpy was noted (Azin and Moghimi 2018). The impact of biomass dose is a crucial factor that must be researched. The scientists found that increasing the quantity of biosorbent from 0.2 to 0.8 g/L was associated with a discernible improvement in the biosorption of dye when the effect of the biosorbent dose or amount (0.2–1.6 g/L) on reactive red 198 was evaluated at room temperature. However, following that, an increase in biosorbent dose did not consistently influence biosorption capability. The improvement in the removal of reactive red 198 with higher amount of biosorbent can be explained by the greater availability of active biosorption sites up to a certain level and after a certain dosage of biosorbent, a saturation point was achieved (Akar et al. 2013).

Ecotoxicity analysis

Ecotoxicity studies are useful in determining how mycoremediation will affect the environment. They ascertain whether employing fungi to break down contaminants is a successful method that doesn't negatively impact other ecosystem inhabitants. The metabolites or byproducts created during mycoremediation can be identified as potential sources of risk with the aid of these tests. Pollutant degradation is the main objective, but it's crucial to make sure the breakdown products don't pose a greater threat than the initial pollutants. They aid in figuring out whether the pollution in the environment is less hazardous after treatment. Mycoremediation is frequently marketed as a green strategy. This assertion is verified by ecotoxicity studies, which determine whether the procedure satisfies safety requirements and laws pertaining to toxicity levels and environmental impact. Over time or in specific situations, some pollutants may break down into chemicals that show toxicity. Ecotoxicity tests support the assessment of mycoremediation's long-term impacts and guarantee that it is an environmentally sound option. In order to evaluate the environmental impact of remediation processes, regulatory organizations frequently demand ecotoxicity studies. Such testing can help demonstrate the efficacy of mycoremediation and secure regulatory approval for large-scale applications. To sum up, ecotoxicity studies are essential for assessing the effectiveness, safety, and environmental impact of mycoremediation methods, thereby guaranteeing that they offer a viable and long-lasting approach to pollutant remediation. Hence, it is worth conducting a toxicity analysis on different animals and plants or to check genotoxicity in the case of a carcinogenic compound.

Table 5 Zoo toxicity of pure dyes versus biologically treated dyes

Tested organism	Dye	Toxicity		Fungi used (species or strain)	Toxicity of treated sample		References
		TU	Toxicity class		TU	Toxicity class	
Daphnia magna	Brilliant green (BG)	141.0	V	*Pleurotus ostreatus* (BWPH)	3.7	III	Przystas et al. 2012; Przystś et al. 2013
				Gloeophyllum odoratum (DCa)	42.1	IV	
				Fusarium oxysporum (G1)	5.3	III	
Daphnia magna	Evans blue (EB)	102.1	V	BWPH	5.9	III	
				DCa	13.3	IV	
				G1	-	Non- toxic	
Daphnia magna	Mixture of BG and EB (1:1 proportion)	139.9	V	BWPH	8.3	III	
				DCa	6.3	III	
				G1	4.5	III	

Table 6 Phytotoxicity pure dyes versus biologically treated dyes on lower plant

Tested organism	Dye	Toxicity		Fungi used (species or strain)	Toxicity of treated sample		References
		TU	Toxicity class		TU	Toxicity class	
Lemna minor	Brilliant green (BG)	87.4	IV	*Pleurotus ostreatus* (BWPH)	–	Non-toxic	Przystas et al. 2012; Przystś et al. 2013
				Gloeophyllum odoratum (DCa)	3.1	III	
				Fusarium oxysporum (G1)	3.7	III	
Lemna minor	Evans blue (EB)	77.1	IV	BWPH	2.4	III	
				DCa	6.3	III	
				G1	8.3	III	
Lemna minor	Mixture of BG and EB (1:1 proportion)	83.4	IV	BWPH	–	Non-toxic	
				DCa	4.7	III	
				G1	–	Non-toxic	

Table 7 Phytotoxicity pure dyes versus biologically treated dyes on higher plants

Tested plant	Biological treatment type	Pure dye and biologically treated dye solution	% germination	Shoot length (cm)	Root length (cm)	References
Zea mais	Control	Water	91 ± 2.02	12.2 ± 1.02	4.26 ± 0.37	Asses et al. 2018
	Untreated	Congo red (200 mg L^{-1})	60 ± 3.52 (∗)	6.5 ± 0.36 (∗)	1.7 ± 0.14 (∗∗)	
	Aspergillus niger	Transformation intermediates	82 ± 3.05 (Ns)	10.9 ± 0.52 (Ns)	3.16 ± 0.21 (Ns)	
Solanum lycopersicum	Control	Water	88 ± 2.08	5.16 ± 0.44	3.13 ± 0.12	
	Untreated	Congo red (200 mg L^{-1})	60 ± 3.78 (∗)	1.8 ± 0.15 (∗∗)	2.06 ± 0.17 (∗)	
	Aspergillus niger	Transformation intermediates	81 ± 2.72 (Ns)	4.66 ± 0.44 (Ns)	3.2 ± 0.15 (Ns)	
Vigna radiata	Control	distilled water	–	–	–	Sanghi and Verma 2013
	Untreated	RB4 dye	57.6 (0.4) a	–	–	
	Basidiomycetous fungus NIOCC #2a	Direct sorption	63.9 (1.7) a,b	–	–	
		Enzyme treated	66.9 (1.7) b	–	–	
		Sorption following enzyme treatment	91.4 (4.5) c	–	–	
Triticum aestivum	Untreated	SIT- Sitara Textile	50	4.26 ± 1.87	4.13 ± 2.02	Bilal et al. 2016
		MAT- Masood Textile	40	3.87 ± 0.63	3.76 ± 2.5	
		KHT- Khyber Textile	50	4.80 ± 2.30	3.89 ± 1.08	
		KAT—Kalash Textile	40	2.78 ± 0.84	3.13 ± 1.12	
	Ganoderma lucidum crude extract of ligninolytic enzymes (MnP 717.7, LiP 576.3, and Laccase 323.2 IU/mL)	SIT- Sitara Textile	70	8.42 ± 2.37	6.14 ± 2.41	
		MAT- Masood Textile	60	7.47 ± 0.32	5.64 ± 1.10	
		KHT- Khyber Textile	80	8.12 ± 2.89	6.21 ± 1.80	
		KAT—Kalash Textile	70	5.56 ± 1.25	4.91 ± 1.19	

Zoo toxicity

For zoo toxicity analysis, the *Daphnia magna* acute immobilization test is the most widely used test and the test is performed according to OECD guideline 211. To conduct this test, less than 24 h neonates of *D.magna* were utilized and were exposed to five different concentrations of pure dye and post-process samples collected at different time intervals. And after 48 h incubation, a higher number of immobile organisms corresponds to higher toxicity (Przystas et al. 2012). The half maximal effective concentration (EC50) is considered as 50% immobilization of the test organism. It is used to categorize treated wastewater into a toxicity class based on the toxicity unit (TU) (Table 5).

Phytotoxicity

The *Lemna minor* growth inhibition test is commonly conducted test in laboratory to assess the toxicity of pollutants towards plants and is performed in accordance with the OECD 221 guidelines (2006) (Table 6). The *L. minor* organisms obtained from the test kits and 3 organisms per well utilized checking the toxicity of 10 mL of test solution. Same as zoo-toxicity test, the five concentrations chosen for analysis. To record the test result, the frond number has been selected as measurable variables to calculate the substance-related effects on vegetative growth. The phytotoxicity test is important because the treated industrial effluent may be recycled and used in farming. Hence, it is important to test the percentage of seeds and roots and shoot of the plant to decide the effectiveness of dye degradation technology and achieve sustainable goals. *Zea mais*, *Triticum aestivum*, and *Vigna radiata* are utilized for phytotoxicity tests. Several dyes also possess carcinogenic potential (Table 7).

Most studies on decolorization do not consider the toxicity analyze of the process products, which is a significant oversight and hinders the correct interpretation of the results. Information that appears in a few publications indicates that the process may lead to the formation of potentially more harmful compounds than the pure dye. The toxicity experiment was carried out to control the inhibition of root growth in *Lectuca sativa* before and after the Procion Red MX-5B treatment via biosorption and biodegradation with the aid of *Aspergillus niger* and *Aspergillus terreus*, taking into account the high sensitivity of plants to poisonous substances. After biosorption treatment with *A.niger*, the growth inhibition percentage decreased. But after biodegradation treatment, an almost tenfold increase in toxicity was observed after 336 h of *A. terreus* treatment (Almeida & Corso 2014).

Limitations of mycoremdiation techniques

As the environmentally friendly, versatility, cost-Effectiveness, biodegradability, minimal site disruption, suitability for In-Situ remediation are conted as the advantages of the mycoremdiation technology. There are certain limitations as well such as [I] Treatment Time: Compared to chemical cleanup techniques, mycoremediation procedures can be somewhat slow. The length of time it takes for contaminants to completely degrade could be extended depending on their complexity and concentration. [II] Specificity: Although fungi have a broad substrate selectivity, some contaminants may not degrade easily or may need particular environmental circumstances to be remedied effectively. This restricts the pollutants or environmental conditions that mycoremediation procedures can be used to. [III] Environmental parameters: Temperature, pH, moisture content, and nutrient availability are some of the environmental parameters that affect the effectiveness of mycoremediation. Unfavourable environmental circumstances can prevent pollutant degradation and fungal growth, necessitating close observation and treatment. [IV] Regulatory Approval: Mycoremediation techniques may face regulatory obstacles in spite of their potential advantages because of worries about their safety, efficacy, and long-term environmental impact. It could be necessary to do a lot of testing and validation before receiving regulatory approval for large-scale adoption. [V] Monitoring and Verification: Keeping track of mycoremediation's advancement and confirming the efficiency of pollutant degradation can be difficult, especially in intricate environmental matrices. Establishing dependable monitoring methods and evaluation procedures is crucial to guaranteeing effective execution and adherence to regulations.

Future perspectives and conclusion

The review paper has emphasized studies on the possible use of mycoremediation techniques for the treatment of wastewater containing dyes. Bioremediation offers several potential advantages over other conventional wastewater treatment techniques. However, it also has several

drawbacks and loopholes that encourage us to expand the scope of our future research. [I] Integration of Nanotechnology: Examining how to combine nanotechnology with mycoremediation methods could improve dye degradation's specificity and efficiency. Fungal enzymes may be transported via nanoparticles, which may also act as catalysts to quicken the breakdown process. [II] Genetic Engineering: The ability to modify fungi to increase their capacity for dye degradation may be made possible by advancements in genetic engineering. This can entail genetically modifying fungus to express particular enzymes or to endure unfavourable environmental circumstances, therefore broadening their range of applications. [III] Bioreactor Design: Efficiency and scalability may be maximized by creating customised bioreactors for mycoremediation procedures. There may be benefits to using continuous-flow systems, immobilized cell reactors, or biofilm reactors in industrial wastewater treatment plants. These include increased throughput, better control over environmental conditions, and simpler integration. [IV] Synergistic Approaches: Researching how mycoremediation works in tandem with other remediation methods like chemical oxidation or phytoremediation may improve the efficacy of treating complicated wastewaters containing dyes. By combining the advantages of each technique, synergistic techniques may be able to accomplish more thorough pollutant reduction. [V] Environmental Monitoring Technologies: The development of cutting-edge monitoring tools, including biosensors or remote sensing methods, may make it easier to track dye degradation processes in real time on location. These technologies have the potential to offer significant insights into the dynamics of mycoremediation and facilitate prompt modifications to maximise therapy efficacy.

In summary, myco-remediation exhibits great potential as an economical and environmentally friendly method of reducing synthetic dye pollution in a range of environmental media. It is clear from a thorough analysis of kinetic studies, toxicity evaluations, and pollutant alleviation mechanisms that fungal-mediated degradation processes have many benefits, including high specificity, broad substrate specificity, and little production of hazardous byproducts. To solve current issues and take advantage of future opportunities in this subject, more research is necessary. Myco-remediation procedures may be more effective and scalable if genetic engineering, nanotechnology, and creative bioreactor design are combined. Still, advanced scientific research is also required to enhance the knowledge for a better understanding of the degradation mechanism of fungal treatment and all factors that have influence on it. This knowledge is necessary to direct the process to get the best results (the highest decolorization as well as detoxification).

Furthermore, the advancement of cutting-edge environmental monitoring technology may make it easier to optimise myco-remediation processes in real time and monitor them, which would increase treatment efficacy overall. Myco-remediation has the potential to become a key component of the sustainable management of dye-contaminated settings if it embraces these opportunities for the future and keeps expanding our knowledge of fungal-mediated dye degradation.

Compared to other traditional wastewater treatment methods, bioremediation provides a number of potential benefits. It uses a less labor-intensive, more economical natural process than other traditional ways. On-site bioremediation can be done without interfering with daily operations. The method also makes sure that harmful pollutants, including colors, completely degrade into safe goods without the need of any harmful chemicals. Additionally, it guarantees that toxins are eliminated without moving to another environmental medium. While there are some clear benefits of bioremediation, there are also some drawbacks.

The optimization of the process in a way that can be effective in non-sterile environment of a wastewater treatment plant is a highly demanding future prospect. Out of the mostly reviewed article, they describe the studies regarding the functionality of various extracellular enzymes such as ligninolytic enzymes and intracellular enzyme such as cytochrome 450 for degradation of various pollutants. The immobilized fungal system or immobilized enzyme system also showed good potential for dye degradation. However, the underlying mechanism for the removal of harmful pollutants via the myco-remediation technique is still elusive and highly requires further research in direction of mechanism findings. To explore and understand the mechanism of myco-remediation of various pollutants at a gene level, the functional genomics or whole proteomic research should be prioritized. The omics technology needs to be utilized to reveal the hidden path of the fungal genetics which are responsible for the degradative process. Conceivably, these studies will have a higher possibility to reveal various genes and their proteins counterparts tangled in the myco-remediation process. From this data, the derived information will

provide assistance to model the genetically improvised fungal strain for additional competent and swift clearance of pollutants from ecosystem.

Furthermore, large-scale bioreactors can be developed using fungi and their enzymes for removal or degradation of pollutants on a wider scale. There is a scope of research specially focusing on optimizing the operating parameters inside the bioreactors for betterment of process. To satisfy the need of finding new isolates, the indigenous fungi developing on polluted sites should be taken into account for further studies as they are gradually naturally adapted to the more concentration of different pollutants besides residing in harsh environment. Different kinds of toxicity tests must be conducted along with the degradation test. It will be good to distinguish the toxic characteristics of water and it will provide the true value of recycled water.

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