Chapter 1
Endophytic Fungi: Role in Dye Decolorization

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1.1 Introduction

Synthetic dyes have become an important part of life as they have several advantages over natural dyes; for example, they are very stable as a result of the formation of covalent bonds with fiber, whereas natural dyes are less permanent and difficult to apply. There are approximate 10,000 synthetic dyes available on market with annual production of 7 × 10^5 metric tons (Campos et al. 2001). Significant amounts of synthetic dyes are used by the textile and dye industries; 15–20% of the dyes used in the dye industry are unable to bind to fabric and are released as effluent and contaminate nearby water sources (Husain 2010). Water is a natural resource that is required in almost all household and industrial uses. Industrial effluents that contain mainly dye compounds are among the serious causes of water pollution, making water unfit for aquatic life (Hassani et al. 2008; Chanyal and Agrawal 2017). Many synthetic dyes are also carcinogenic and toxic to human and aquatic life as they are made up of compounds like benzidine and aromatic compounds. Cleavage of some of the most widely used commercial dyes, azo dyes, resulted in the formation of amine, which is mutagenic to humans (Asgher et al. 2006). Direct discharge of contaminants from several industries to the environment is the main cause of water pollution, so the removal of these compounds from the environment is essential for sustainable development (Aksu and Donmez 2005; Balaji et al. 2012).

The methods used for dye treatment are classified into three categories: physical, chemical, and biological methods (Robinson et al. 2001). The physical and chemical methods are quite expensive not very effective for the treatment of dyes from wastewater (Si et al. 2013). Because of their disadvantages, like their high cost, associated waste disposal problems, and lower adaptability, these methods are not

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well suited for the treatment of dye-contaminated water (Asgher et al. 2008). Hence, the production of cost-effective, environmentally friendly, and efficient biological methods is necessary for effluent treatment.

Bioremediation-based methods using microorganisms for the treatment of effluent could be an efficient method as several bacteria and especially fungi and their enzymes are reported to have potential in decolorizing textile dyes (Forgacs et al. 2004). Bioremediation as a technology enjoys wide public support owing to its low cost and environmental friendliness. Among microorganisms, endophytes that reside in plants grown in contaminated sites may be a promising biological organism for the elimination of dye or for the decolorization of dye produced by several industries. Other important functions of endophytes include the ability to augment the thermal and salinity tolerance of host plants, increasing their ability to live in extreme environmental conditions (Redman et al. 2002). Rodriguez et al. (2004) reported that some tropical trees can increase their resistance by hosting endophytic microorganisms. Hence, bioremediation, which involves the use of microorganisms in the degradation or absorption of pollutants, is one of the most effective alternatives for the removal or reduction of industrial waste (Mcmullan et al. 2001; Singh et al. 2014). Most microorganisms, especially fungi and their enzymes, have the potential to degrade dyes by producing enzymes like laccases (Forgacs et al. 2004). Several researchers have reported that laccases produced by endophytic fungi have the ability to degrade azo dyes (Chanyal and Agrawal 2017; Ngieng et al. 2013; Novotny et al. 2004). Ngieng et al. (2013) reported on 20 endophytic fungi from *Melastoma malabathricum* with the ability to decolorize 5 different azo dyes to varying degrees. This chapter provides an overview of various forms of dye degradation using endophytic fungi, presents a biotechnological approach to using these fungi, and discusses their future prospects.

1.2 Endophytes

The groups of microorganisms that inhabit different parts of plant tissues without causing any disease symptoms are known as endophytes (Gouda et al. 2016; Schulz and Boyle 2005; Specian et al. 2012). There are no apparent symptoms of disease found in plants hosting endophytes. Hence, endophytes exhibit strong positive associations with their host plant (Nair and Padmavathy 2014).

Endophytes are well known to produce a wide variety of bioactive compounds, including antibiotics, antitumor and immunosuppressive agents, plant growth hormones, and biological substances like enzymes, alkaloids, and vitamins, which can play a vital role in the pharmaceutical and agriculture industries (Uzma et al. 2018; Mishra et al. 2017; Wu et al. 2010). Endophytes are reported to produce compounds having the ability to inhibit bacterial and fungal pathogens and could help in protecting plants against phytopathogens (Mishra et al. 2016; Rya et al. 2007; Staniek et al. 2008; Rai et al. 2014). Interestingly, few endophytes share the compounds produced by plants as well (Kumara et al. 2014; Shweta et al. 2014). These findings demonstrate that endophytes are present within plant tissues and subsist as reservoirs of bioactive metabolites (Tan and Zou 2001; Priti et al. 2009).

Endophytes are categorized into bacteria and fungi. More than 200 bacterial genera have been identified as endophytes distributed among the phyla Actinobacteria, Proteobacteria, and Firmicutes (Golinska et al. 2015). Among these, the genus *Streptomyces* from the phylum Actinobacteria is the most dominant of genera that have been isolated in large volume from medicinal plants as endophytes (Zothanpuia et al. 2018; Zhao et al. 2011; Golinska et al. 2015). Endophytic fungi are classified into clavicipitaceous and nonclavicipitaceous. Clavicipitaceous fungi are those that infect certain grasses present in cool regions, and nonclavicipitaceous fungi are isolated from healthy tissues of nonvascular plants like ferns and their allies, conifers, and angiosperms. Ascomycota and Basidiomycota represent the two main groups of nonclavicipitaceous fungi (Jalgaonwala et al. 2011; Bhardwaj and Agrawal 2014).

1.3 Dyes

Dyes are complex colored organic compounds mainly used in the textile, leather, paper, and food industries (Harvey and Keith 1983). Since dyes are the major component used in these industries, the effluents discharged are mainly composed of dye compounds that act as the main source of organic pollutants released into the environment that disturb normal biotic as well as abiotic systems (Muthezhilan et al. 2014). Dyes can exist in many different formed, but they include a minimum of one azo (N=N) bond. For instance, dyes having one N=N bond are known as azo and monoazo dyes, whereas dyes having two and three N=N bonds are known as diazos and triazos, respectively. Azo groups linked with naphthalene and benzene rings give dyes their color and make various shades and intensities possible (Zollinger 1991). Dyes are broadly divided into synthetic and natural dyes, and do not have a definite chemical structure. Chromophores give fibers their color, whereas auxochromes fixed colors on fibers (Banat et al. 1996; Welham 2000). Dye processing occurs largely in three steps: preparation, dyeing, and finishing. Different types of dye processing are carried out based on the nature of the fiber and the properties of the dyes, like the chemical structure, fixing property compatibility with the materials to be used, classification, and pigments used (Guaratini and Zanoni 2000). Large amounts of chemical compounds are used in each step of dye processing (Moore and Ausley 2004).

Dyes cause serious problems related to the release of industrial effluents and the removal of dyes and other chemicals pollutants (Balaji et al. 2012). Most dyes can affect human beings and animals by causing allergies, cardiovascular problems, gastrointestinal problems, DNA damage, and cancer (Harvey and Keith 1983; Mittal et al. 2006). To address these problems, many researchers are trying to develop a simple, eco-friendly, and cost-effective techniques for dye degradation, but this remains a very difficult and complex challenge (Pant et al. 2008).

1.3.1 Types of Dyes

1.3.1.1 Textile Dyes and Their Importance

Over 100,000 colors of synthetic dyes are produced commercially, and over 7×10^5 tons of dyes are produced every year worldwide (Zollinger 1987). Throughout the world, dyes are heavily utilized in the textile, cosmetic, paper, pharmaceutical, and food industries along with additives in the petroleum industry (Husain 2010). Synthetic dyes are broadly used in the textile and dyeing industries. When dyes are processed, approximately 15–20% of the dyes does not bind with fibers and as a result is lost in effluent (Husain 2010). Maas and Chaudhari (2005) suggested that around the world, approximately 280,000 tons of textile dyes are released from industrial sewage every year. The released textile dyes are transferred in rivers or lakes, which can cause water pollution at very low concentrations of 1 ppm (O'Neill et al. 1999). The accumulation of dye in water can reduce sunlight penetration, which in turn can reduce photosynthetic activity. Moreover, accumulated dyes unfavorably influence biological oxygen demand (BOD), chemical oxygen demand (COD), and dissolved oxygen, which creates a toxic environment for aquatic organisms (Khan and Bhawana 2013; Sen et al. 2016). Most dyes have a hard structure and are of synthetic origin, so bleaching dyes is complicated.

Natural Dyes

Natural dyes are obtained from natural resources like different parts of plants, animals, insects, and minerals without application of any chemical treatment. Indigo dye from the plant *Indigofera tinctoria*, lawsone obtained from *Lawsonia mermis*, carajurin obtained from *Bignonia chica*, and carotenoids are examples of natural dyes (Vankar 2000). Synthetic dyes are widely used in various industries, but they are also known mutagens, allergens, and carcinogens, whereas natural dyes do not have any toxic effects. Dyes obtained from natural resources like plants, animals, or minerals are very easy to wash and clean, and for this reason natural dyes are very eco-friendly (Vankar 2000). In addition to their dyeing properties, natural dyes also have a broad range of medicinal properties. These days, there is growing awareness of the use of natural dyes and dye producer plants. Owing to their nontoxic nature, medicinal values, and less harmful side effects, natural dyes are now applied commonly in everyday food products and in the pharmaceutical industry (Chengaiah et al. 2010; Shahid et al. 2013).

In India, over 400 plants can produce dye. For instance, a brilliant, naturally occurring yellow dye is produced from turmeric, which also has strong antiseptic activity to cure skin ailments (Siva 2007). Natural dyes are commonly applied in food coloring, leather, natural protein fibers like wool, silk, and cotton textiles, and even in drugs and cosmetic products owing to their nontoxicity. Due to the evolution of synthetic dyes, the use of natural dyes worldwide in textiles has been limited to artisan or craftsman uses, small-scale or cottage-level dyers, and printers, and some producers manufacture environmental friendly dyes for textile production (Chavan 1995). Natural dyes require a compound known as a mordant used to set dyes on fabric, which prevents the dye from bleeding or being washed out easily. Mordants facilitate chemical reactions for the absorption of dyes between dyes and fibers (Siva 2007).

Most natural dyes are found from plants that produce various colors. Most plant parts like the seeds, leaves, bark, roots, flowers, fruits, and so forth produce dyes. Interestingly, 2000 pigments are made by different plant parts. Of these, only 150 have been commercially sold on the market. In India, approx. 450 taxa are known to produce dyes, of which the 50 best-known plants produce natural dyes. Briefly, Siva (2007) reported that most dyes are obtained from roots ($n = 10$), followed by wood ($n = 8$), flowers and fruits ($n = 7$), leaves ($n = 5$), bark ($n = 4$), seeds, and gum and resins ($n = 3$). To date, few dyes have been synthesized from natural sources; for instance, few plants, like *Lithospermum erythrorhizon* and *Bixa Orellana*, can be used to derive dyes for lipstick and indigo for eye shadow. Siva (2007) demonstrated that the occurrence of dyes in plants varies depending on the age of the plant and the season. Many plants, such as *Punica granatum* L., which have high antimicrobial potential due to the occurrence of high amounts of tannins, can be used to extract natural dyes. Moreover, several other plant dyes, such as lawsone, commonly known as henna obtained from *Lawsonia inermis* L., Juglone from walnut, and lapachol from alkanet, demonstrated antibacterial and antifungal properties (Siva 2007). Another advantage of natural dyes is that some have antimicrobial potential against pathogens. Singh et al. (2005) reported on the antimicrobial activity of five natural dyes (*Acacia catechu, Kerria lacca, Quercus infectoria, Rubia cordifolia*, and *Rumex maritimus*) against *Klebsiella pneumonie*, *Escherichia coli*, *Proteus vulgaris*, and *Pseudomonas aeruginosa*. Of these, *Quercus infectoria*, a natural dye, showed the highest antimicrobial activity (Singh et al. 2005).

Synthetic Dyes

Synthetic dyes are widely used in various industries such as textiles, leather, beauty care products, food, pharmaceuticals, and paper printing. The most toxic compounds that create environmental pollution include azo, antraquinone, heterocyclic, triphenylmethane, and phthalocyanine dyes. Interestingly, 10–15% of dyes are removed in wastewater in these industries while dyeing and washing textiles (Husain 2010). This wastewater can cause several diseases around the world. Moreover, the release of wastewater can pollute both ground and surface water, which may lead to various health issues in both humans and animals because they are considered very toxic, mutagenic, and carcinogenic. Therefore, it is immensely important to search for alternative methods to degrade dyes easily from wastewater treatment systems. The degradation of dyes using physical and chemical methods is not very effective owing to the high costs and time and because the method could be methodologically demanding (Ben Younes et al. 2012). Nowadays, most researchers are trying to use microorganisms to degrade dyes (Eichlerova et al. 2005).

Of the 100,000 commercially available dyes, at least 10–15% of the used dye traps in the environment in the form of wastes become major environmental pollutants (Zollinger 1987; O'Neill et al. 1999; Robinson et al. 2001). Among synthetic dyes, azo reactive dyes are the most prevalent types that are soluble in water. Azo dyes have the greatest range of color structures and colors among the synthetic dyes and are usually resistant to biodegradation by aerobic methods. Most of these dyes become toxic only after being released into aquatic environments, where they may be converted into harmful carcinogenic amines (Spadaro et al. 1992; Chung and Stevens 1993). Hence, they are considered xenobiotic compounds due to their resistance to natural microbiological degradation (Stolz 2001). There are more than 3000 azo dyes, of which Maxilon Blue GRL, Astrazon Red GTLN, and Sandolan Yellow are widely used in certain industries like textiles, leather, cosmetics, food coloring, and paper production (Elbanna et al. 2010). It was estimated that approximately 10% of dyes do set in fiber during the dyeing process and are released directly into the environment, causing major harm (Asad et al. 2007) and complications like mutagenicity, genotoxicity, and carcinogenicity to living beings (Puvaneswari et al. 2006).

White rot fungi are commonly used as decomposers of lignin and have the potential to degrade various organic pollutants, including pesticides, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls and synthetic dyes (Bezalel et al. 1997; Sack et al. 1997; Novotny et al. 2000; Pointing 2001). They are commonly used in nonspecific, free-radical-mediated processes that utilize enzymes to degrade lignin and other structurally similar compounds (Chagas and Durrant 2001). Many researchers have reported on the decolorization and degradation of synthetic dyes from various ligninolytic fungi such as *Phanerochaete chrysosporium* (Couto et al. 2000; Podgornik et al. 2001; Conneely et al. 2002; Moldes et al. 2003), *Trametes versicolor* (Swamy and Ramsay 1999a, b; Borchert and Libra 2001; Martins et al. 2003), *Pleurotus ostreatus* (Shin et al. 1997; Rodrigues et al. 1999; Novotny et al. 2001), and *Bjerkandera adusta* (Heinfling et al. 1998; Heinfling-Weidtmann et al. 2001; Jarosz-Wilkołazka et al. 2002). In total, 20 fungal endophytes have been obtained from *Melastoma malabathricum* and examined for their potential to decolorize azo dyes such as congo red, methyl red, orange G, and an anthraquinone dye, Remazol Brilliant Blue R (RBBR). Of these, the isolated *Marasmius cladophyllus* strain MS8 has decolorized RBBR, methyl red, congo red, and orange G in percentages of 97%, 56%, 48%, and 33%, respectively (Ngieng et al. 2013).

1.4 Biosorption and Bioaccumulation

Among all the methods for the treatment of wastewater, adsorption has been regarded as an efficient and low-cost process for the treatment of dyes mixed with effluents released by industry. The removal of textile dyes from wastewater using fungal biomass is an attractive option as it might reduce the overall cost of the treatment process (Saraf and Vaidya 2015). Biosorption is the combination of biomass solutes that cannot use any metabolic energy or transport in the binding process.

This binding process may occur suddenly where live biomass is used. However, both living and dead biomass can be used in biosorption (Tobin et al. 1994).

The degradation of dyes has been mostly performed by microbial isolates originating from soils polluted with dyes, effluents from industry, or marine sources (Saratale et al. 2006; Abedin 2008; Gou et al. 2009). For instance, Kabbout and Taha (2014) studied the biosorption of methylene blue by the dead fungal biomass of *Aspergillus fumigates* and optimized the conditions for better absorption. *Aspergillus niger* and *Rhizopus stolonifer* showed the ability to remove dyes like Congo red and bromophenol blue respectively by biosorption (Fu and Viraraghavan 2001; Zeroual et al. 2006). Bayramoglu and Arica (2007) studied the native and heat-treated fungal biomass of *Trametes versicolor* for the removal of two benzidine dyes, direct red 128 and direct blue −1 using different parameters. The biosorption activity of the heat-treated and native biomass of *T. versicolor* was 152.3 and 101.1 mg/g for direct blue −1 and 225.4 and 189.7 mg/g for the removal of direct red. Iqbal and Saeed (2007) reported that the uptake efficiency of RBBR by immobilized *Phanerochaete chrysosporium* biomass in loofa sponge was much better than that of free fungal biomass with enhanced uptake efficiency of RBBR. The value of loofa sponge–immobilized biomass increased (18.6%) compared to free fungal biomass. Marcharchand and Ting (2017) showed that *Trichoderma asperellum* growing on fewer nutrients can retain its dye-decolorizing efficiency. *Trichoderma asperellum* has been grown in synthetic medium with different concentrations such as 20%, 50%, 75%, and 100%, and shown an ability to perform biosorption. This is also a good cost-effective strategy to use on fungi for dye removal; this method can help to lower the cost of cultivating the biomass of Ta for dye removal activities isolated at lower concentrations (20%, 50%, and 75%). This result demonstrated that lower nutrient levels might be useful in cultivating the biomass of Ta for dye removal activities (Marcharchand and Ting 2017) (Table 1.1).

However, endophytes associated with plants have been much less explored for their biosorbent activity. Ting et al. (2016) recovered an endophytic *Diaporthe* sp. fungus from *Portulaca* weed and explored it for its potential activity in biodegradation and biosorption in triphenylmethane (TPM) dyes. The live cells of *Diaporthe* sp. showed stronger decolorizing activity against malachite green, crystal violet, and methyl violet with decolorizing efficiencies (%) of 87.80%, 84.87%, and 78.81%, respectively. Additionally, Ting et al. (2016) reported that the decolorization of live cells is far better than the decolorizing efficiency (18.82%, 39.88%, 48.32%) of dead cells.

Bioaccumulation is explained as the accumulation of pollutants or any xenobiotic substance by actively growing cells by metabolism (Aksu and Donmez 2005). Aksu and Donmez (2005) suggested that some fungi, like *Candida tropicalis*, have the ability to remove different dyes like Remazol Black B and Remazol Blue using a bioaccumulation process. Similarly, *Saccharomyces cerevisiae* can remove dyes like Remazol Blue, Remazol Black B, and Remazol Red RB by bioaccumulation (Aksu 2003). Taskin and Erdel (2010) also showed the efficiency of fungi soilborne *Aspergillus niger* in decolorizing textile dye Reactive Black 5 through bioaccumulation.

Table 1.1 Biodegradation of various synthetic dyes by endophytic fungi

Source	Name of organism	Type of dye	Mechanism	Reference
M. malabathricum	*Marasmius cladophyllus*	Remazol Brilliant Blue R (RBBR), Orange G, Congo red, and Methyl red	–	Ngieng et al. (2013)
P. hispidum Sw	*Phlebia* spp.	Reactive Blue 19 and Reactive Black 5	Absorption	Bulla et al. (2017)
H. annuus L	*P. formosus*	Reactive Blue 19 and Reactive Black 5	Absorption	Bulla et al. (2017)
Canavalia rosea, *Ipomoea pescaprae* and Spinifex spp.	*Fusarium* spp.	Yellow MR, Blue M2R, Black-B, Red BSID, Manenta MP, Blue MR, Orange M2R, Orange 3R and Brown GR	–	Muthezhilan et al. (2014)
Pigieon pea	*Myrothecium verrucaria*	Congo red, Methyl orange, Methyl red, and Crystal violet	–	Sun et al. (2017)
Decayed wood	*Ganoderma cupreum*	Reactive violet 1	Biodegradation	Gahlout et al. (2013)
Fagus sylvatica	*Fomes fomentarius*	Remazol Brilliant Blue R (RBBR)	–	Eichlerova et al. (2005)
Fagus sylvatica	*Oudemansiella mucida*	Remazol Brilliant Blue R (RBBR) and Orange G	–	Eichlerova et al. (2005)
Liquidambar styraciflua and *Quercus nuttallii*	*Pleurotus cystidiosus*	Remazol Brilliant Blue R (RBBR)	–	Eichlerova et al. (2005)
Acer pseudosieboldianum	*Trichaptum abietinum*	Remazol Brilliant Blue R (RBBR) and Orange G	–	Eichlerova et al. (2005)

1.5 Enzymes Involved in Biodegradation of Dyes

Lignin is easily degraded by most fungi owing to their extracellular secretion of nonspecific and nonselective enzymes. These enzymes are laccases, manganese peroxidases, and lignin peroxidases, which can work together to produce H_2O_2 and secondary metabolites. (Kirk and Farrell 1987; Levin et al. 2004). Similarly, due to their nonspecific mechanisms, these fungi are able to degrade lignin and various other pollutants such as PAHs, polychlorinated biphenyls, dioxins, chlorinated phenols, explosives, dyes, and pesticides (Pointing 2001). Some researchers have reported on the ability of laccases, manganese peroxidases, and lignin peroxidases to decolorize dyes (Cripps et al. 1990; Podgornik et al. 2001; Pointing 2001). Cha et al. (2001) reported that most fungi have cytochrome P-450 monooxygenase, which is involved in organic pollutant degradation.

Laccases are multicopper enzymes with the ability to oxidize phenolic and nonphenolic lignin-related compounds. Moreover, laccases have applications in bioremediation as well as other biotechnological applications (Yang et al. 2017). They are broadly distributed in fungi, bacteria, insects, and plants. They can catalyze the oxidation of a broad range of substrates, including mono-, di-, and polyphenols, ascorbate, and methoxyphenols through the concurrent reduction of oxygen to water. Most widely studied laccases are of fungal origin. They are primarily produced by ascomycetes, basidiomycetes, and deuteromycetes, of which white-rot basidiomycetes are regarded as the most proficient laccase producers (Arora and Sharma 2010; Si et al. 2013; Yang et al. 2017; Zhuo et al. 2017). Laccases are also commonly used in bleaching, pulping, dye decolorization, biosensing, food technology, and wastewater treatment (Campos et al. 2016). Endophytic fungi also have the potential to decolorize dyes discharged in various industries.

Laccases are among the major enzymes produced by endophytic fungi for decolorizing dye. Muthezhilan et al. (2014) reported on the fungal endophyte *Fusarium* sp. strain AEF17 isolated from the *Ipomoea pescaprae* plant showing laccase enzyme production. The laccase purified from this strain had the potential to decolorize nine different textile dyes. The maximum decolorization activity was found in blue M2R (BM2R), orange M2R(OM2R), and black-B (BB), followed by limited decolorization activity by red BSID (RBSID), yellow MR(YMR), blue MR (BMR), magenta MP (MMP), brown GR (BGR), and orange 3R (O3R) and decolorization. In another study, a fungal endophyte known as *Myrothecium verrucaria* was isolated from pigeon pea that has the potential to produce laccase enzyme. In the presence of ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonate), the isolate *Myrothecium verrucaria* exhibited significant decolorization potential toward methyl orange, Congo red, crystal violet, and methyl red) (Sun et al. 2017). Endophytic fungi *Phlebia* spp. isolated from *P. hispidum* Sw. and *P. formosus*, obtained from *H. annuus* L., were active in biodegradation of textile dyes. They displayed the ability to degrade Reactive Black 5 and Reactive Blue 19 textile dyes. After 30 days of treatment, isolated *Phlebia* spp. and *P. formosus* showed 90% and 70% degradation of black and blue dye, respectively. *Phlebia* spp. showed the highest production of extracellular laccase, which suggests a role of the enzyme in the decolorization of the blue and black textile dyes (Bulla et al. 2017). The strain *Ganoderma cupreum* AG-1 isolated from decayed wood showed the potential to produce lignolytic enzymes and the capacity to decolorize around 19 different azo dyes in a pH range of 4.5–6. The *Ganoderma cupreum* strain AG-1 was also found to produce laccase and manganese peroxidase. *G. cupreum* AG-1 showed a capacity to produce large amounts of laccase, which indicates its role in decolorizing dyes (Gahlout et al. 2013). A white-rot fungis from Argentina, *Coriolus versicolor* f. *antarcticus*, showed potential for the production of various extracellular enzymes like laccase, lignin peroxidase, and manganese peroxidase on solid medium, which have the ability to decolorize different dyes such as malachite green, azure B, poly R478, anthraquinone blue, Congo red, and xylidine (Levin et al. 2004). Levin et al. (2004) suggested that the strain *Coriolus versicolor* f. *antarcticus* could be used as a candidate in biodecoloration processes. Fungal endophytes associated with *Melastoma malabathricum* exhibited the ability to decolorize three azo dyes: methyl red, Congo red, and orange G. Among all the endophytic isolates recovered from *M. malabathricum*, a basidiomycete fungus, *Marasmius cladophyllus*, decolorized 97% of RBBR dye, followed by 56% decolorization of methyl red (Table 1.1).

1.6 Conclusion

Fungus-mediated biodegradation or removal of dye from wastewater involves either the use of pure enzymes or biosorption. This chapter discussed the importance of endophytic fungi in both biosorption and enzyme-mediated removal of dyes using endophytic fungi.

Laccases from endophytic fungi have demonstrated their potential in degrading various types of dyes. Additionally, many studies on fungal biosorbents have suggested that biosorbents represent an emerging and promising solution to conventional practices. Fungal endophytes have been much less explored for their ability to remove dyes using a biosorption approach. However, many studies have reported on purified laccases from endophytic fungi for their potent activity in degrading dyes. Nevertheless, it is essential to search for endophytic fungal strains that are very eco-friendly and nontoxic that can degrade various dyes easily.

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References

Abedin RMA (2008) Decolorization and biodegradation of crystal violet and malachite green by *Fusarium solani* (Martius) Saccardo. A comparative study on biosorption of dyes by the dead fungal biomass. AEJB 1:17–31

Aksu Z (2003) Reactive dye bioaccumulation by *Saccharomyces cerevisiae*. Process Biochem 38:1437–1444

Aksu Z, Donmez G (2005) Combined effects of molasses sucrose and reactive dye on the growth and dye bioaccumulation properties of *Candida tropicalis*. Process Biochem 40:2443–2454

Arora DS, Sharma RK (2010) Ligninolytic fungal laccases and their biotechnological applications. Appl Biochem Biotechnol 160(6):1760–1788

Asad S, Amoozegar MA, Pourbabaee AA, Sarbolouki MN, Dastgheib SM (2007) Decolorization of textile dyes by newly isolated halophilic and halotolerant bacteria. Bioresour Technol 98:2082–2088

Asgher M, Shah SAH, Ali M, Legge RL (2006) Decolorization of some reactive textile dyes by white rot fungi isolated in Pakistan. World J Microbiol Biotechnol 22:89–93

Asgher M, Bhatti HN, Ashraf M, Legge RL (2008) Recent developments in biodegradation of industrial pollutants by white rot fungi and their enzyme system. Biodegradation 19:771–783

Balaji V, Vinayagamoorthi D, Palanisamy A, Anbalagan S (2012) Degradation of reactive Red HE7B and Yellow FN2R dyes by fungal isolates. J Acad Indus Res 1(3):132–136

Banat IM, Nigam P, Singh D, Marchant R (1996) Microbial decolorization of textile-dye-containing effluents: a review. Bioresour Technol 61:103–103

Bayramoglu G, Arica MY (2007) Biosorption of benzidine based textile dyes “Direct Blue 1 and Direct Red 128” using native and heat-treated biomass of *Trametes versicolor*. J Hazard Mater 143:135–143

Ben Younes S, Bouallagui Z, Sayadi S (2012) Catalytic behaviour and detoxifying ability of an atypical homotrimeric laccase from the thermophilic strain *Scytalidium thermophilum* on selected Azo and Triarylmethane dyes. J Mol Catal B Enzym 79:41–48

Bezalel L, Hadar Y, Cerniglia CE (1997) Enzymatic mechanisms involved in phenantrene degradation by white-rot fungus *Pleurotus ostreatus*. Appl Environ Microbiol 63:2495–2501

Bhardwaj A, Agrawal P (2014) A review fungal endophytes: as a store house of bioactive compound. World J Pharm Pharm Sci 3:228–237

Borchert M, Libra JA (2001) Decolorization of reactive dyes by the white rot fungus *Trametes versicolor* in sequencing batch reactors. Biotechnol Bioeng 75:313–321

Bulla LMC, Polonio JC, Portela-Castro ALB, Kava V, Azevedo JL, Pamphile JA (2017) Activity of the endophytic fungi *Phlebia sp*. and *Paecilomyces formosus* in decolourisation and the reduction o reactive dyes’ cytotoxicity in fish erythrocytes. Environ Monit Assess 189(88):1–11

Campos R, Kandelbauer A, Robra KH, Cavaco-Paulo A, Gubitz GM (2001) Indigo degradation with purified laccases from *Trametes hirsuta* and *Sclerotium rolfsii*. J Biotechnol 89:131–139

Campos PA, Levin LN, Wirth SA (2016) Heterologous production, characterization and dye decolorization ability of a novel thermostable laccase isoenzyme from *Trametes trogii* BAFC 463. Process Biochem 51:895–903

Cha CJ, Doerge DR, Cerniglia CE (2001) Biotransformation of Malachite Green by the fungus *Cunninghamella elegans*. Appl Environ Microbiol 67:4358–4360

Chagas EP, Durrant LR (2001) Decolorization of azo dyes by *Phanerochaete chrysosporium* and *Pleurotus sajorcaju*. Enzym Microb Technol 29:473–477

Chanyal S, Agrawal PK (2017) Decolorization of textile by laccase from newly isolated endophytic fungus *Daldinia* sp. Kavaka 48(1):33–41

Chavan RB (1995) Revival of natural dyes—a word of caution to environmentalists. In: Symposium proceedings eco-friendly textile processing. India and Japan, IIT, Delhi, p 83–186

Chengaiah B, Rao KM, Kumar KM, Alagusundaram M, Chetty CM (2010) Medicinal importance of natural dyes—a review. Int J PharmTech Res 2(1):144–154

Chung KT, Stevens SE (1993) Decolorization of azo dyes environmental microorganisms and helminthes. Environ Toxicol Chem 12:2121–2132

Conneely A, Smyth WF, McMullan G (2002) Study of the white-rot fungal degradation of selected phthalocyanine dyes by capillary electrophoresis and liquid chromatography. Anal Chim Acta 451:259–270

Couto SR, Rivela I, Munoz MR, Sanroma’n A (2000) Stimulation of ligninolytic enzyme production and the ability to decolorize Poly R-478 in semi-solid-state cultures of *Phanerochaete chrysosporium*. Bioresour Technol 74:159–164

Cripps C, Bumpus JA, Aust SD (1990) Biodegradation of azo and heterocyclic dyes by *Phanerochaete chrysosporium*. Appl Environ Microbiol 56:1114–1148

Eichlerova I, Homolka L, Lisa L, Nerud F (2005) Orange G and Remazol Brilliant Blue R decolorization by white rot fungi *Dichomitus squalens*, *Ischnoderma resinosum* and *Pleurotus*. Chemosphere 60:398–404

Elbanna K, Hassan G, Khider M, Mandour R (2010) Safe biodegradation of textile azo dyes by newly isolated lactic acid bacteria and detection of plasmids associated with degradation. J Bioremed Biodegr 1:1–6

Forgacs E, Cserhati T, Oros G (2004) Removal of synthetic dyes from wastewaters: a review. Environ Int 30:953–971

Fu Y, Viraraghavan T (2001) Fungal decolourization of dye wastewaters: a review. Bioresour Technol 79:251–262

Gahlout M, Gupte S, Gupte A (2013) Optimization of culture condition for enhanced decolorization and degradation of azo dye reactive violet 1 with concomitant production of ligninolytic enzymes by *Ganoderma cupreum* AG-1. 3 Biotech 3(2):143–152

Golinska P, Wypij M, Agarkar G, Rathod D, Dahm H, Rai M (2015) Endophytic actinobacteria of medicinal plants: diversity and bioactivity. Anton Van Leeuwen 108:267–289

Gou M, Qu Y, Zhou J, Ma F, Tan L (2009) Azo dye decolorization by a new fungal isolate *Penicillium* sp. QQ and fungal-bacterial cocultures. J Hazard Mater 170:314–319

Gouda S, Das G, Sen SK, Shin HS, Patra JK (2016) Endophytes: a treasure house of bioactive compounds of medicinal importance. Front Microbiol 7:1538

Guaratini CCI, Zanoni MVB (2000) Textile dyes. Química Nova 23(1):71–78

Harvey JW, Keith AS (1983) Studies of the efficacy and potential hazards of methylene blue therapy in aniline-induced haemoglobinaemia. Br J Haematol 54(1):29–41

Hassani AH, Mirzayee R, Nasseri S, Borghei M, Gholami M, Torabifar B (2008) Nanofiltration process on dye removal from simulated textile wastewater. Int J Environ Sci Technol 5(3):401–408

Heinfling A, Martı'nez MJ, Martínez AT, Bergbauer M, Szewzyk U (1998) Transformation of industrial dyes by manganese peroxidases from *Bjerkandera adusta* and *Pleurotus eringii* in a manganese-independent reaction. Appl Environ Microbiol 64:2788–2793

Heinfling-Weidtmann A, Reemtsma T, Storm T, Szewzyk U (2001) Sulfophthalimide as major metabolite formed from sulfonated phthalocyanine dyes by the white-rot fungus *Bjerkandera adusta*. FEMS Microbiol Lett 203:179–183

Husain Q (2010) Peroxidase mediated decolorization and remediation of wastewater containing industrial dyes: a review. Rev Environ Sci Biotechnol 9(2):117–140

Iqbal M, Saeed A (2007) Biosorption of reactive dye by loofa sponge-immobilized fungal biomass of *Phanerochaete chrysosporium*. Process Biochem 42:1160–1164

Jalgaonwala RE, Mohite BV, Mahajan RT (2011) Natural products from plant associated endophytic fungi. J Microbiol Biotechnol Res 1:21–32

Jarosz-Wilkołazka A, Rdest-Kochman˜ ska J, Malarczyk E, Wardas W, Leonowicz A (2002) Fungi and their ability to decolorize azo and antraquinonic dyes. Enzym Microb Technol 30:566–572

Kabbout R, Taha S (2014) Biodecolorization of textile dye effluent by biosorption on fungal biomass materials. Phys Procedia 55:437–444

Khan RP, Bhawana FMH (2013) Microbial decolorization and degradation of synthetic dyes: a review. Rev Environ Sci Biotechnol 12(1):75–97

Kirk TK, Farrell RL (1987) Enzymatic "combustion": the microbial degradation of lignin. Annu Rev Microbiol 41:465–505

Kumara MP, Soujanya KN, Ravikanth G, Vasudeva R, Gane- shaiah KN, Uma Shaanker R (2014) Rohitukine, a chromone alkaloid and a precursor of flavopiridol, is produced by endophytic fungi isolated from *Dysoxylum binectariferum Hook.f* and *Amoora rohituka* (Roxb). Phytomedicine 21:541–546

Levin L, Papinutti L, Forchiassin F (2004) Evaluation of Argentinean white-rot fungi for their ability to produce lignin-modifying enzymes and decolorize industrial dyes. Bioresour Technol 94:169–176

Maas R, Chaudhari S (2005) Adsorption and biological decolourization of azo dye Reactive Red 2 in semicontinuous anaerobic reactors. Process Biochem 40(2):699–705

Marcharchand S, Ting ASY (2017) *Trichoderma asperellum* cultured in reduced concentrations of synthetic medium retained dye decolourization efficacy. J Environ Manag 203(1):542–549

Martins MAM, Lima N, Silvestre AJD, Queiroz MJ (2003) Comparative studies of fungal degradation of single or mixed bioaccessible reactive azo dyes. Chemosphere 52:967–973

Mcmullan G, Mehan C, Conneely A, Kirby N, Robinson T, Nigam P, Banat IM, Marchant R, Smyth WF (2001) Microbial decolourisation and degradation of textile dyes. Appl Microbiol Biotechnol 56(1–2):81–87

Mishra VK, Passari AK, Singh BP (2016) In vitro antimycotic and biosynthetic potential of fungal endophytes associated with *Schima Wallichii*. In: Kumar P et al (eds) Current trends in disease diagnostics. Springer International Publishing, Basel, pp 367–381

Mishra VK, Passari AK, Chandra P, Leo VV, Kumar B, Gupta VK, Singh BP (2017) Determination and production of antimicrobial compounds by *Aspergillus clavatonanicus* strain MJ31, an endophytic fungus from *Mirabilis jalapa* L. using UPLC-ESI-MS/MS and TD GC-MS. PLoS One 12(10):1–24. https://doi.org/10.1371/journal.pone.0186234

Mittal A, Mittal J, Kurup L, Singh A (2006) Process development for the removal and recovery of hazardous dye erythrosine from wastewater by waste materials – bottom ash and de-oiled soya as adsorbents. J Hazard Mater 138(1):95–105

Moldes D, Couto SR, Cameselle C, MA S'n (2003) Study of the degradation of dyes by MnP of *Phanerochaete chrysosporium* produced in a fixed-bed bioreactor. Chemosphere 51:295–303

Moore SB, Ausley LW (2004) Systems thinking and green chemistry in the textile industry: concepts, technologies and benefits. J Clean Prod 12:585–601

Muthezhilan R, Vinoth S, Gopi K, Jaffar Hussain A (2014) A dye degrading potential of immobilized laccase from endophytic fungi of coastal sand dune plants. Int J Chem Tech Res 6(9):4154–4160

Nair DN, Padmavathy S (2014) Impact of endophytic microorganisms on plants, environment and humans. Sci World J 2014:11

Ngieng NS, Zulkharnain A, Roslan HA, Husaini A (2013) Decolorization of synthetic dyes by endophytic fungal flora isolated from Senduduk Plant (*Melastoma malabathricum*). Biotechnology 2013:260730

Novotny C, Erbanova P, Cajthaml T, Rothschild N, Dosoretz C, Sasek V (2000) *Irpex lacteus*, a white rot fungus applicable to water and soil bioremediation. Appl Microbiol Biotechnol 54:850–853

Novotny C, Rawal B, Bhatt M, Patel M, Sasek V, Molitoris HP (2001) Capacity of *Irpex lacteus* and *Pleurotus ostreatus* for decolorization of chemically different dyes. J Biotechnol 89:113–122

Novotny C, Svobodova K, Kasinath A, Erbanova P (2004) Biodegradation of synthetic dyes by *Irpex lacteus* under various growth conditions. Int Biodeter Biodegr 54:215–223

O'Neill C, Hawkes F, Hawkes D, Lourenco N, Pinheiro H, Delee W (1999) Colour in textile effluents-sources, measurement, discharge consents and simulation: a review. J Chem Technol Biotechnol 74:1009–1018

Pant D, Singh A, Satyawali Y, Gupta RK (2008) Effect of carbon and nitrogen source amendment on synthetic dyes decolourizing efficiency of white-rot fungus, *Phanerochaete chrysosporium*. J Environ Biol 29:79–84

Podgornik H, Poljansek I, Perdih A (2001) Transformation of Indigo carmine by *Phanerochaete chrysosporium* ligninolytic enzymes. Enzym Microb Technol 29:166–172

Pointing SB (2001) Feasibility of bioremediation by white-rot fungi. Appl Microbiol Biotechnol 57:20–33

Priti V, Ramesha BT, Singh S, Ravikanth G, Ganeshaiah KN, Suryanaraynan TS, Shaanker U (2009) How promising are endophytic fungi as alternative sources of plant secondary metabolites? Curr Sci 97(4):477–478

Puvaneswari N, Muthukrishnan J, Gunasekaran P (2006) Toxicity assessment and microbial degradation of azo dyes. Indian J Exp Biol 44:618 626

Rai M, Agarkar G, Rathod D (2014) Multiple applications of endophytic *Colletotrichum* species occurring in medicinal plants, in novel plant bioresources: applications in food, medicine and cosmetics. In: Gurib-Fakim A (ed) Novel plant bioresources. Wiley, Chichester, pp 227–236

Redman RS, Sheehan KB, Stout RG, Rodriguez RJ, Henson JM (2002) Thermotolerance conferred to plant host and fungal endophyte during mutualistic symbiosis. Science 298:1581

Robinson T, McMullan G, Marchant R, Nigam P (2001) Remediation of dyes in textile effluent a critical review on current treatment technologies with a proposed alternative. Bioresour Technol 77:247–255

Rodrigues E, Pickard A, Vazquez-Duhalt R (1999) Industrial dye decolorization by laccases from ligninolytic fungi. Curr Microbiol 38:27–32

Rodriguez RJ, Redman RS, Henson JM (2004) The role of fungal symbioses in the adaptation of plants to high stress environments. Mitig Adapt Strat Global Change 9:261–272

Rya RPK, Germaine A, Franks DJ, Ryan DN (2007) Bacterial endophytes: recent developments and applications. FEMS Microbiol Lett 278:1–9

Sack U, Heinze TM, Deck J, Cerniglia CE, Martens R, Zadrazil F, Fritsche W (1997) Comparison of phenantrene and pyrene degradation by different wood-decaying fungi. Appl Environ Microbiol 63:3919–3925

Saraf S, Vaidya VK (2015) Comparative study of biosorption of textile dyes using fungal biosorbents. Int J Curr Microbiol App Sci 2:357–365

Saratale GD, Kalme SD, Govindwar SP (2006) Decolorisation of textile dyes by *Aspergillus ochraceus* (NCIM-1146). IJBT 5:407–410

Schulz B, Boyle C (2005) The endophytic continuum. Mycol Res 109:661–686

Sen SK, Raut S, Bandopadhyay P, Raut S (2016) Fungal decolouration and degradation of azo dyes: a review. Fungal Biol Rev 30(3):112–133

Shahid M, Mohammad F, Islam S (2013) Recent advancements in natural dye applications: a review. J Clean Prod 53:310–331

Shin KS, Oh IK, Kim CHJ (1997) Production and purification of Remazol brilliant blue decolorizing peroxidase from the culture filtrate of *Pleurotus ostreatus*. Appl Environ Microbiol 63:1744–1748

Shweta S, Shivanna MB, Gurumurthy BR, Shaanker U, Santhosh Kumar TR, Ravikanth G (2014) Inhibition of fungal endophytes by camptothecine produced by their host plant, *Nothapodytes nimmoniana* (Grahm) Mabb. (Icacinaceae). Curr Sci 107:994–1000

Si J, Peng F, Cui BK (2013) Purification, biochemical characterization and dye decolorization capacity of an alkali-resistant and metal tolerant laccase from *Trametes pubescens*. Bioresour Technol 128:49–57

Singh R, Jain A, Panwar S, Gupta D, Khare SK (2005) Antimicrobial activity of some natural dyes. Dyes Pigments 66(2):99–102

Singh R, Singh P, Sharma R (2014) Microorganism as a tool of bioremediation technology for cleaning environment: a review. Proc Int Acad Ecol Environ Sci 4(1):1–6

Siva R (2007) Status of natural dyes and dye yielding plants in India. Curr Sci 92(7):916–925

Spadaro JT, Gold MH, Renganathan V (1992) Degradation of azo dyes by the lignin degrading fungus *P chrysosporium*. Appl Environ Microb 58:2397–2340

Specian V, Sarragiotto MH, Pamphile JA, Clemente E (2012) Chemical characterization of bioactive compounds from the endophytic fungus *Diaporthe helianthi* isolated from *Luehea divaricata*. Braz J Microbiol 43:1174–1182

Staniek A, Woerdenbag HJ, Kayser O (2008) Endophytes: exploiting biodiversity for the improvement of natural product-based drug discovery. J Plant Interact 3:75–98

Stolz A (2001) Basic and applied aspects in the microbial degradation of azo dyes. Appl Microbiol Biotechnol 56:69–80

Sun J, Guo N, Niu LL, Wang QF, Zang YP, Zu YG et al (2017) Production of laccase by a new *Myrothecium verrucaria* MD-R-16 isolated from Pigeon Pea [*Cajanus cajan* (L.) Millsp.] and its application on dye decolorization. Molecules 22:673

Swamy J, Ramsay JA (1999a) The evaluation of white rot fungi in the decoloration of textile dyes. Enzym Microb Technol 24:130–137

Swamy J, Ramsay JA (1999b) Effects of Mn2+ and NHþ 4 concentrations on laccase and manganese peroxidase production and Amaranth decoloration by *Trametes versicolor*. Appl Microbiol Biotechnol 51:391–396

Tan RX, Zou WX (2001) Endophytes: a rich source of functional metabolites. Nat Prod Rep 18:448–459

Taskin M, Erdel S (2010) Reactive dye bioaccumulation by fungus *Aspergillus niger* isolated from the effluent of sugar fabric-contaminated soil. Toxicol Ind Health 26(4):239–247

Ting ASY, Lee MVJ, Chow YY, Cheong SL (2016) Novel exploration of endophytic *Diaporthe* sp. for the biosorption and biodegradation of triphenylmethane dyes. Water Air Soil Pollut 227:109

Tobin JM, White C, Gadd GM (1994) Metal accumulation by fungi: applications in environment biotechnology. J Ind Microbiol 13:126–130

Uzma F, Hashem A, Murthy N, Mohan HD, Kamath PV, Singh BP, Venkataramana M, Gupta VK, Siddaiah CN, Chowdappa S, Alqaeawi AA, Abd-Allah EF (2018) Endophytic fungi—alternative sources of cytotoxic compounds: a review. Front Pharmacol 9(309):1–37. https://doi.org/10.3389/fphar.2018.00309

Vankar PS (2000) Chemistry of natural dyes. Resonance 5(10):73–80

Welham A (2000) The theory of dyeing (and the secret of life). J Soc Dye Colour 116:140–143

Wu X, Monchy S, Taghavi S, Zhu W, Ramos J, Van der Lelie D (2010) Comparative genomics and functional analysis of niche specific adaptation in *Pseudomonas putida*. FEMS Microbiol Rev 35(2):299–323

Yang J, Li W, Ng TB, Deng X, Lin J, Ye X (2017) Laccases: production, expression, regulation, and applications in pharmaceutical biodegradation. Front Microbiol 8:832

Zeroual Y, Kim BS, Kim CS, Blaghen M, Lee KM (2006) Biosorption of Bromophenol blue from aqueous solutions by *Rhizopus stolonifer* biomass. Water Air Soil Pollut 177:135–146

Zhao J, Shan T, Mou Y, Zhou L (2011) Plant-derived bioactive compounds produced by endophytic fungi. Mini Rev Med Chem 11:159–168

Zhuo R, Yuan P, Yang Y, Zhang S, Ma F, Zhang X (2017) Induction of laccase by metal ions and aromatic compounds in *Pleurotus ostreatus* HAUCC 162 and decolorization of different synthetic dyes by the extracellular laccase. Biochem Eng J 117:62–72

Zollinger H (1987) Colour chemistry: synthesis, properties of organic dyes and pigments. VCH Publishers, New York, pp 92–100

Zollinger H (1991) Color chemistry: synthesis, properties and application of organic dyes and pigments. Angew Chem Int Ed 496:456–980

Zothanpuia PAK, Leo VV, Kumar B, Chnadra P, Nayak C, Hashem A, Abd Allah EF, Alqarawi AA, Singh BP (2018) Bioprospection of actinobacteria derived from freshwater sediments for their potential to produce antimicrobial compounds. Microb Cell Fact 17(1):68. https://doi.org/10.1093/chromsci/bmy050