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Bioremoval of industrial dyes using different microorganisms

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ABSTRACT

Textile dyeing effluents are a major source of water pollution because of their pigmentation and the creation of harmful or potentially cancer-causing intermediate compounds, such as aromatic amines originating from azo dyes. The extensive industrial expansion and uncontrolled rapid growth of current textile manufacturing facilities have led to the discharge of large volumes of untreated textile dye effluents, which contain a variety of hazardous contaminants like dyes, metal ions, heavy metals, organic substances, and other toxic materials. Bioremediation is a promising alternative to conventional treatment methods for textile dyeing effluents. It is a cost-effective and environmentally friendly approach that uses biological organisms to degrade and remove pollutants from the environment. This review evaluates the performance and typical attributes of bioremediation and stands out as a practical and effective option for addressing the treatment of textile dyes. It also highlights the current challenges and anticipated advancements in the field of bioremediation techniques for the removal of dye-containing wastewater in the future.

KEYWORDS

Bioremediation; Azo dyes; Dyeing; Decolorization; Biosorption

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Introduction

Water is essential for life and a valuable resource for human civilization. However, there are millions of individuals who do not have access to safe and clean drinking water. Wastewater recovery and recycling have grown increasingly important due to rising water demand and water pollution. The textile industry ranks among the significant contributors to wastewater effluent, primarily attributed to its substantial water usage during wet processing procedures [1]. This effluent includes a range of substances, such as dyes, acids, alkalis, hydrogen peroxide, starch, and surfactant dispersing agents.

Textile dyeing and finishing generates around 17-20% of global industrial wastewater. The removal efficiency of pollutants during both primary and secondary treatment processes is limited due to their recalcitrant nature. This leads to their release into the aquatic environment, where they have the potential to accumulate in soil sediments and infiltrate the drinking water supply chain. Synthetic dyes have been identified as capable of producing aromatic compounds with increased toxicity, including mutagenic and carcinogenic properties [2]. The unregulated discharge of textile wastewater poses significant health risks and environmental harm. Typically, textile wastewaters exhibit coloration, with dye concentrations ranging from 10 to 200 mg/L. Some dyes remain visible in water even at concentrations as low as 1 mg/L. These wastewater discharges frequently contain pigmented substances along with hazardous chemicals, which can diminish soil fertility and severely impede the photosynthetic capabilities of plants.

Synthetic dyes can exert adverse effects on plant growth, including the inhibition of seed germination, reduced seedling survival rates, and stunted shoot and root growth. Additionally, the presence of these dyes diminishes water's oxygen solubility and clarity, potentially posing a threat to aquatic organisms. Dyes may also prevent algal growth and photosynthesis by limiting the penetration of light. The effect of synthetic dyes extends beyond plants and other organisms, impacting human well-being due to their toxic nature [3,4]. Stringent regulations now exist for the discharge of textile effluents, driven by their recognized hazards to both the environment and society.

Recently, the conservation of water resources has become a pressing concern, prompting increased attention towards wastewater recovery and reuse. Various physicochemical methods are available for wastewater treatment, including adsorption, coagulation, membrane filtration, ion exchange, sonication, and plasma treatment. However, these approaches come with drawbacks, such as high operational and energy costs, the generation of substantial sludge, and the production of harmful by-products. There is a growing interest in technologies that can yield reusable water, eliminate toxicity, mineralize aromatic compounds, and minimize sludge production [5,6]. Consequently, the utilization of living organisms, such as plants and microorganisms, has gained prominence as an alternative to conventional processes for wastewater treatment. The primary focus of this paper lies in harnessing microorganisms for the absorption and degradation of toxic substances found in wastewater, representing a novel approach to remediate contaminated water.

Pollution of Toxic Dyes

Industries such as textiles and pigment-based sectors, including paints, photography, plastics, printing, tannery, rubber, paper, pharmaceuticals, and cosmetics, release a substantial volume of colored waste in the form of dyes into the environment. Globally, there are over 10,000 different dyes

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and pigments commercially available, with an annual production exceeding 700,000 tons. Remarkably, approximately 20% of these dyes are lost during the dyeing and printing processes, with nearly half of that quantity ultimately being discharged into the environment [7]. The wastewater from textile industries comprises a diverse array of organic and inorganic dyes, with the majority belonging to the category of azo and synthetic dyes. In recent times, the escalating utilization of reactive azo dyes, which account for 30% of the total dye market, has emerged as a significant source of concern in terms of water pollution [8].

Toxic Effect of Industrial Dye Molecules

Textile dyes and their associated residues, particularly aromatic amines, unquestionably possess a high level of toxicity, leading to significant health concerns for a wide range of living organisms, including humans. These dyes can have various harmful effects, including being allergenic, carcinogenic, teratogenic, and mutagenic. They can damage the genetic material (DNA) of living organisms. Numerous textile dyes are manufactured using toxic chemicals like azo, nitro, benzidine, and anthraquinone, which can be converted into even more toxic forms in sediments, aquatic environments, and living organisms [9,10]. Certain azo dyes have been linked to several types of cancers in humans, such as splenic sarcomas, hepatocarcinomas, nuclear anomalies, and chromosomal aberrations. Prolonged exposure to dye waste can lead to a range of health problems in humans, including skin itchiness, headaches, nausea, diarrhea, muscle and joint pain, fatigue, dizziness, breathing difficulties, irregular heartbeats, loss of concentration in adults, dark circles under the eyes, red cheeks and ears, hyperactivity, learning problems in children. These health concerns highlight the importance of proper handling and disposal of textile dyes and their residues to minimize the risks to both human health and the environment [11]. Additionally, efforts to develop safer and more sustainable dyeing processes and alternatives are essential to reduce the harmful impact of textile dyeing on the planet and its inhabitants.

The persistent presence of dyes in aquatic environments can result in bioaccumulation and biomagnification along the food chain, leading to an increase in dye concentrations within organisms as they progress up the chain. This phenomenon poses a significant risk to aquatic plants, animals, and ultimately, humans due to the enduring and harmful nature of dye molecules. The unnatural coloration of wastewater containing dyes can have a profound impact on the photosynthetic processes of aquatic autotrophs by impeding the penetration of sunlight [12]. This disruption affects the entire aquatic ecosystem. The intricate chemical structure of synthetic dyes with long chains renders them stable, resistant to degradation, and toxic to the natural environment. Consequently, the substantial discharge of untreated industrial effluents containing dyes into the environment, including water bodies, presents a severe threat to the integrity of the biological ecosystem [13].

Biological Systems Involved in the Discoloration of Industrial Toxic Dyes

As concerns about wastewater treatment continue to grow, regulations are becoming increasingly stringent, prompting the development of numerous innovative methods to enhance wastewater treatment efficiency. Nevertheless, given the intricate nature of pollutants, there isn't a single "one-size-fits-all" bioremediation technique capable of restoring all polluted environments. Microorganisms possess remarkable versatility when it comes to eliminating pollutants from wastewater by biodegrading persistent compounds [14]. Bioremediation, employing various microbes such as bacteria, fungi, yeasts, and algae, has demonstrated the ability to decolorize and fully degrade many dyes under specific environmental conditions. Recent research endeavors have focused extensively on microbiological approaches to address the decolorization of dyes [15].

Biological degradation methods can be categorized according to their oxygen requirements into three main types: aerobic, anaerobic, and anoxic (which combine elements of both aerobic and anaerobic processes). The anoxic method is particularly prevalent, with the initial anaerobic step being utilized to treat dye wastewater with high Chemical Oxygen Demand (COD), followed by subsequent processes for treating the resulting effluents with lower COD levels [16]. When considering the mechanisms involved in the degradation of dye wastewater, two primary methods emerge biosorption and biodegradation. Fungi and algae are commonly employed for this purpose. The cell walls of these microorganisms contain thiol, phosphate, amino, and carboxyl groups that bind to azo compounds, facilitating a rapid process that is typically completed within a few hours [17,18].

In biodegradation, a complete process known as mineralization takes place, wherein organic compounds are transformed into water and carbon dioxide. During the biodegradation of textile dyes by bacterial strains, one limitation can be the diffusion of substrates into the bacterial cell. Fungal strains, on the other hand, tend to overcome this issue [19]. Among various fungal strains, white-rot fungi have proven to be highly effective at biodegradation. These fungi produce ligninolytic enzymes capable of binding to a wide range of textile dyes [20]. Enzymes such as lignin peroxidases (LiP), laccases, tyrosinases (Try), manganese peroxidases (MnP), NADH-DCIP reductase, azoreductase, and hexane oxidases can be produced by various organisms to reduce azo compounds. Laccases and azoreductases, in particular, have demonstrated significant potential for decolorizing a broad spectrum of synthetic dyes [21]. Sometimes, under unfavorable environmental conditions, some cellular enzymes in organisms may undergo conversion into enzymes capable of degrading dyes. For instance, flavin reductase from E. coli can act as an azoreductase.

Dye decolorization by bacteria

Diverse groups of bacteria exhibit the capability to decolorize industrial azo and synthetic dyes, and they can do so under various conditions, including aerobic, anaerobic, and facultative anaerobic environments. Anaerobic bacteria, in particular, prove highly effective at color removal due to their production of azoreductases, which cleave azo bonds (-N=N-) and generate aromatic amines, albeit with mutagenic properties [22]. Under oxygen-deprived conditions, azo dyes serve as a terminal electron acceptor. In contrast, activated sludge processes primarily operate aerobically, but they are less efficient when it comes to color removal. Bacterial decolorization, on the other

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hand, offers several advantages [23,24]. It can achieve a higher degree of biodegradation and mineralization, making it relevant for a vast range of azo dyes. Bacterial degradation is also known for its speed, surpassing other organisms in terms of efficiency. Bacteria display remarkable pH stability and resilience under challenging conditions.

Dye decolorization by fungi

Fungi are increasingly recognized as highly promising organisms for effectively breaking down and mineralizing stubborn textile dyes due to their potent enzymatic arsenal, characterized by the extracellular ligninolytic enzyme system. Fungi's unique distinctive physical characteristics and a wide range of metabolic capabilities further contribute to their effectiveness in this regard [25]. The process of fungal degradation encompasses a combination of adsorption and enzymatic degradation, or sometimes a synergistic interplay between the two. Bio-adsorption serves a crucial role in the decolorization of dyes by living fungi, and enzymatic degradation also significantly contributes to this process [26]. Various enzymes come into play during this degradation, including azoreductases, laccases, manganese peroxidases, and lignin peroxidases. However, it's important to note that the precise mechanism behind azo dye decolorization by fungi remains an area of ongoing research and investigation [27].

Fungal biodegradation, under optimal conditions encompassing suitable pH, temperature, and decolorization duration, can accomplish a remarkable color reduction exceeding 90%. However, it's worth noting that fungi exhibit limited pH stability, which constitutes a notable drawback. An illustrative example of a fungal strain showcasing effective dye decolorization is Ceriporia lacerata, a type of white-rot fungus found in decomposed mulberry branches [28].

Dye decolorization using yeast

Research into yeast-based decolorization and dye degradation has been relatively limited, with a primary focus on biosorption mechanisms. However, yeasts show considerable promise in the decolorization of various azo dyes for bioremediation purposes, owing to several advantageous characteristics [29]. These characteristics include their high capacity for accumulating dyes, including heavy metals like lead and cadmium (II), as demonstrated by Fairhead and Thöny-Meyer in 2012 [30]. Yeasts also exhibit faster growth rates and more efficient decolorization capabilities when compared to filamentous fungi. It's important to acknowledge that wastewater sludge contains a diverse range of yeast strains, although they typically constitute a minor fraction of the microorganisms present in activated sludge.

Furthermore, yeast demonstrates the capacity for enzymatic degradation with enhanced stability. To summarize, yeast-based approaches offer distinct advantages for the removal of color and breakdown of dyes, especially in the bioremediation of textile dyes [31]. These advantages stem from their exceptional capabilities, including robust growth, efficient decolorization, and adaptability to challenging environmental conditions.

Dye decolorization by algae

Algae, widely distributed in various ecosystems, are gaining increased recognition for their role in degrading textile dyes. Algae primarily function as adsorbents, setting themselves apart from synthetic commercial adsorbents. They hold the advantage of treating larger significant volumes of dye wastewater as a result of their substantial biomass content, and they possess the capacity for biodegradation mechanisms [32]. Utilizing algae in the treatment process is generally more straightforward compared to other organisms for several reasons: a) utilization of dyes for growth: Algae have the ability to utilize dyes as a nutrient source for their own growth. b) transformation of dyes into other intermediates or CO2 and water: algae are capable of transforming dyes into different compounds or breaking them down into carbon dioxide and water. c) adsorption of chromophores on algae: algae can also adsorb chromophores, which are responsible for the color in dyes [33].

It's essential to recognize the fundamental distinction between biosorption and biodegradation. Biosorption pertains to the process of adsorbing dyes from water onto a solid phase, often referred to as bio-adsorbents [34]. In contrast, biodegradation involves enzymatically transforming one compound into another. In summary, Algae play a crucial role in the breakdown of textile dyes, offering several advantages like their efficient adsorption capacity, capability to handle substantial volumes of dye wastewater, and their potential for biodegradation [35]. These mechanisms are indeed distinct from one another, with biosorption involving the adsorption of dyes onto solid surfaces and biodegradation entailing enzymatic transformation processes.

Application of Consortia-Based Mixed Bacterial Bioremediation

Monocultures are limited in their ability to decolorize a narrow range of industrial dyes and are often less efficient in achieving complete degradation. To achieve high rates of decolorization, degradation, and mineralization of dye wastewater, mixed microbial cultures are essential [36]. Mixed cultures offer several advantages over monocultures when it comes to synthetic dye degradation:

Synergistic Activity: Within a mixed culture, individual strains may target different positions on the dye molecule or utilize metabolites produced by other strains, resulting in a synergistic breakdown of the dye [37].

Adaptability: Microorganisms within mixed cultures possess a higher degree of adaptability to cope with toxic waste and develop resistance, which enables them to transform a variety of toxic chemicals into less harmful forms [38].

Complete Degradation: Mixed cultures can produce a range of enzymes that collectively facilitate the complete degradation of chemical compounds, ensuring a more thorough and comprehensive breakdown of pollutants [39].

Bacterial consortia are widely employed for the decolorization of azo dyes, and they are particularly favored in this context. Bacteria exhibit rapid multiplication rates and thrive under diverse conditions, including aerobic, anaerobic, and anoxic environments, as well as in harsh conditions like high salinity and wide pH and temperature fluctuations [40]. The effectiveness of decolorization achieved by bacterial consortia is often compared to that of monocultures, and this efficiency may be attributed to the involvement of a process commonly called quorum sensing. Quorum sensing is a process

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by which bacteria control their gene expression within their community [41]. Several factors directly influence bacterial decolorization, including temperature, pH, dye structure, inoculum concentration, dye concentration, carbon and nitrogen sources, electron donors, agitation speed, oxygen transfer rate, redox mediators, and NaCl concentrations. These factors collectively impact the efficiency of the decolorization process by bacterial consortia.

Specially adapted bacterial strains, often isolated from sites contaminated with dyes, exhibit remarkable efficiency in the removal process due to their ability to thrive in diverse and extreme environmental conditions [42]. In contrast, there is a paucity of reports concerning the decolorization of dyes by yeast, algal, and fungal consortia. An alternative strategy involves harnessing the collaborative and synergistic activity of a fungal-bacterial consortium, offering an effective approach for effectively eliminating a wide range of contaminants [43]. Several studies have revealed that co-cultures of fungi and bacteria exhibit heightened efficiency and stability in the degradation of a mixture of complex organic compounds into smaller molecules [44].

Bioremediation stands out as a widely adopted and effective approach for treating dye effluents, yet it does come with certain challenges that require attention. The primary issues associated with textile effluents typically revolve around color, Chemical Oxygen Demand (COD), and other non-biodegradable components [45,46]. While conventional methods can now mitigate Biological Oxygen Demand (BOD) and COD in textile wastewater, bioremediation alone may not suffice for treating all substances present. In such cases, the combination of bioremediation with other treatment methods becomes essential, extending the capacity to remove a broader spectrum of pollutants from the wastewater [47,48]. These amines exhibit significant diversity in their chemical properties, making it challenging for biological treatment to completely remove all amines present in textile dye waters. Another important consideration is the issue of excess sludge production, which has the potential to cause environmental problems [49,50]. This excess sludge needs to be managed effectively to minimize its environmental impact.

Conclusions

Bioremediation stands as an environmentally friendly strategy to mitigate the repercussions and harmful effects stemming from the intermediate byproducts generated by textile effluent. Utilizing both pure cultures and consortia in bioremediation offers an effective and dependable means to mineralize and diminish the toxicity associated with dyes. These organisms employ diverse mechanisms to detoxify dyes, with a particular emphasis on enzyme-mediated bioremediation.

Currently, there is a growing emphasis on the formulation of such consortia, primarily because they demonstrate resilience when exposed to adverse and challenging conditions. Moreover, optimizing various parameters becomes imperative to enhance the efficiency of these consortia while simultaneously safeguarding the environmental well-being and the health of all life forms.

Disclosure statement

No potential conflict of interest was reported by the authors.

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