Bioremediation of Anthraquinone Dyes: The role of *Candida tropicalis* in Textile Waste Management

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***Abstract*—The textile industry has experienced rapid growth due to increased global demand for new materials and clothing, resulting in the extensive use of synthetic dyes such as anthraquinones. Although these dyes are inexpensive and colorful, their persistence and toxicity raise serious environmental concerns, especially with regard to water quality and the health of aquatic ecosystems. This review of environmental pollution problems that emerge with the use of anthraquinone dyes points toward some serious case encountered around the world including in India, China, Bangladesh, Turkey, and Brazil among others. It would prove a breakthrough for the future utilization of dye as an element contributing to remediation with specific microorganisms like *Candida tropicalis*. This yeast has shown superior capabilities in the degradation of anthraquinone dyes through photodynamic and enzymatic mechanisms, thus bioremediating hazardous compounds by converting them into less harmful. However, there is a challenge if lack of nutrients and varying environmental conditions posing a significant limitation to the expansion of bioremediation on a larger scale. Improving growth conditions, using biosurfactants, and genetic engineering can boost *C. tropicalis* performance in bioremediation. By developing these strategies, we can work towards a more sustainable textile industry that minimizes its environmental footprint while safeguarding aquatic life and human health.**

***Key words*—Bioremediation, Anthraquinone, Textile, *Candida tropicalis*, Dyes**

INTRODUCTION

The textile industry has grown a lot because of the rising world population and demand for clothing [1]. This strong growth made it necessary to improve how production systems work. Factories often started using synthetic chemical dyes like azo dyes, anthraquinone, and phthalocyanines because they are cheap and colorful [2]. But using these dyes has caused concern for the environment, especially water quality [3]. Wastewater with dyes has been linked to the death of aquatic life. It also increases heavy metals in the environment, which can harm human health and wildlife [4].

Synthetic organic dyes, such as anthraquinones, are a major concern due to their large volumes and difficulty in degradation [5]. These dyes persist in the environment, causing harm over [6]. Many medical research studies have addressed environmental pollution caused by dyes. For example, Gujarat, India, faced pollution from dyeing industries in 2019 [7]. Similarly, the Yangtze River in China experienced dye pollution in 2020 [8], while Dhaka, Bangladesh in 2021, faced significant pollution from textile dyeing industries, leading to water and soil contamination [9]. In 2022, Turkey, also struggled with dye pollution [10], followed by the Brazilian Amazon in 2023 [11]. These widespread cases highlight the urgent need for developing alternative methods to tackle dye pollution in India.

Bioremediation, the use of microorganisms to degrade dye, is gradually becoming the remedy for the negative effects of dye pollution. *Candida tropicalis* is one of the most promising microorganisms with the ability to biodegrade anthraquinone dyes [12]. The present review attempts to describe the bioremediation potentials of *Candida tropicalis* against anthraquinone, its mode of action, the extent of its bioremediation capabilities, and its possible use in the bioremediation of dyes polluted environments.

ANTHRAQUINONE DYE

Synthetic anthraquinone dyes come from intermediates like anthraquinone sulfonic acid and nitro anthraquinone. These are made by sulfonating and nitrating anthraquinone. These dyes are widely utilized in various industries, particularly textiles, due to their vibrant colors and stability [13]. A key production method is making anthraquinone sulfonic acid, which is an important base for many acid anthraquinone dyes [13], and the production of nitroanthraquinone, which can be further reduced to aminoanthraquinine, another important dye precursor [14]. Additionally, bromamic acid is synthesized from 1-aminoanthraquinone and serves as an important intermediate [15].

Types of Anthraquinone Dye

Different acid dyes, such as azo dyes and surfactant-type dyes, have been made. Azo acid dyes are created using diazotized aromatic amine sulfonic and carboxylic acids. They are known for their bright colors and good fastness [16]. Surfactant-type acid dyes, which include a long-chain alkane tail and an anionic chromophore head, have been developed to improve dyeing properties at lower temperatures, promoting better exhaustion rates and color fastness [17]. Disperse dyes, which have strong affinity for polyester fibers and excellent fastness, can be used in non-aqueous media like supercritical carbon dioxide [18]. Vat dyes and intermediates can give pigments with excellent tinctorial properties, good lightfastness, durability, and overspray fastness properties, but lack the necessary properties for automotive quality pigments [19].

Anthraquinone Dye as an Environmental Pollutant

Anthraquinone dyes pose a serious environmental problem due to their reinforced structure, making them difficult to degrade naturally [5]. Anthraquinone dyes are more toxic than azo dyes, causing harm to humans and the environment due to residual dyes in water or on material surfaces [20]. Anthraquinone dye, a synthetic dye often presents in wastewater, blocks light and hinders photosynthesis, harming aquatic life [21]. Anthraquinone dyes are toxic environmental pollutant due to their stable complex structure, which allows them to persist in water. Their residual presence poses varying degrees of harm to both humans and the environment, necessitating effective degradation methods [20]. Anthraquinone dyes, like Reactive Blue 19, are major environmental pollutants due to their high solubility in water and toxicity, causing harmful wastewater in textile processing. They pose risks as carcinogenic or mutagenic substance, impacting ecosystems and human health [22].

Bioremediation of Anthraquinone

The bioremediation of anthraquinone dyes, which are persistent in the environment, can be effectively done using biological methods such as nanoparticles, bacteria, fungi, and biocatalysts. These approaches leverage the natural degradation capabilities of microorganisms and engineered materials to remove these hazardous compounds from wastewater. Bimetallic Ni-Zn nanoparticles, synthesized from Ficus exasperata leaf extract, showed a maximum adsorption capacity of 50.08 mg/g for anthraquinone dye, proving their effectiveness in dye removal [23]. The strain Bacillus sp. JF4 demonstrated significant degradation of Reactive Blue 19, achieving almost complete breakdown under optimal conditions, highlighting its potential for treating anthraquinone dye-laden wastewater [24]. White-rot fungi, such as *Trametes polyzona*, have also shown high decolorization rates (70-90%) for anthraquinone dyes, emphasizing the role of fungal enzymes like laccase biocatalysts has been proposed as a promising method for enhancing the treatment of anthraquinone dyes in bioreactors, achieving effective degradation rates [25]. While these bioremediation strategies show promise, challenges remain in scaling these methods for industrial applications, particularly regarding the stability and reusability of biocatalysts and the efficiency of microbial strains under varying environmental conditions.

Bioremediation potential of *Candida tropicalis*

Candida tropicalis biofilms can be effectively reduced using natural AQs like rubiadin and rubiadin-1-methyl ether (R-IME) in conjunction with light exposure. Sequential light irradiation combined with AQs resulted in a biofilm mass reduction of up to 82% when paired with antifungal agents like Amphotericin B [26]. Reactive oxygen species (ROS), especially superoxide radicals, are key in the mechanism of biofilm reduction [27]. Candida species, including *C. tropicalis*, are adept at degrading various pollutants, including heavy metals and hydrocarbons, due to their high biodegradability and ease of cultivation [12]. The metabolic pathways of *C. tropicalis* allow it to transform hazardous compounds into non-toxic forms, showcasing its potential in environmental cleanup efforts [28].

Mode of Action of *Candida tropicalis*

The bioremediation of anthraquinone dyes by *Candida tropicalis* involves multiple biochemical processes, mainly the production of reactive oxygen species (ROS) and enzymatic degradation. This yeast species demonstrates significant potential in degrading anthraquinone dyes through both photodynamic and enzymatic mechanisms.

1. *Photodynamic Mechanism*

Candida tropicalis biofilms can be effectively reduced by natural anthraquinones, like rubiadin-1-methyl ether, when exposed to light. The primary action involves the generation of superoxide radical anions (O2-) and singlet oxygen (1O2), which contribute to the degradation of biofilm structures [27][28]. Sequential light irradiation enhances the photodynamic effect, achieving up to 82% reduction in biofilm mass when combined with antifungal agents [27].

2. *Enzymatic Degradation*

The enzymatic activity of *Candida tropicalis* involves laccase production, which helps break down anthraquinone dyes, resulting in significant color removal and lower chemical oxygen demand [29]. The degradation products include low molecular weight phenolic compounds, indicating a transformation of the dye into less harmful substances [29].

EXPERIMENTAL APPROACHES

The enhancement of bioremediation processes involving *Candida tropicalis* has been approached through various experimental strategies, focusing on optimizing growth conditions, utilizing biosurfactants, and employing genetic engineering techniques. These methods aim to improve the efficiency of *C. tropicalis* in degrading pollutants, particularly hydrocarbons.

1. ***Optimization of Growth Conditions***

   C. tropicalis demonstrates strong biodegradation potential for petroleum oil, thriving across a broad pH range (4-11), with optimal growth at pH 4. Glucose and yeast extract enhance biomass formation and degradation capacity. Multi-factorial studies highlight oil concentration as a key factor in bioremediation efficiency [30].

2. ***Use of Biosurfactants and Nanoparticles***

   The production of biosurfactants by *Candida tropicalis* enhances the degradation of complex hydrocarbons like indeno(1,2,3-cd) pyrene, with optimization achieved through response surface methodology. Iron nanoparticles, biosynthesized from mint leaf extract, enhance degradation rates when used in combination with *C. tropicalis* [31].

3. *Genetic Engineering and Omics Approaches*

Genetic engineering and omics technologies (genomics, proteomics) are being explored to improve the metabolic pathways of *C. tropicalis*, potentially boosting its resilience and efficiency in bioremediation [32]. While these experimental approaches show promise, challenges remain in scaling these methods for widespread application, particularly in diverse environmental conditions. Further research is required to overcome these limitations and improve the practical use of *C. tropicalis* in bioremediation efforts.

CHALLENGES IN SCALING THE EXPERIMENTAL APPROACHES

The success of *Candida tropicalis* in bioremediation depends largely on nutrient availability in the contaminated environment, which may be scarce in natural settings [33]. Variable factors like temperature and pH can impact microbial metabolism and biodegradation rates, making it challenging to translate laboratory results to real-world applications [34]. Laboratory-scale successes often do not translate to larger scales due to the complexity of microbial interactions in diverse environments. The bioavailability of pollutants and the survival of non-native species are key factors that require further investigation [35]. Effective bioremediation may need a mix of methods, such as bioaugmentation and biostimulation, along with advanced engineering and monitoring tools to ensure success at different sites [36]. The use of genetically modified organisms, including engineered strains of *Candida*, faces strict regulations that can limit their deployment in bioremediation efforts [33].

CONCLUSION

The growth in the textile industry has led to a lot of environmental challenges, especially with regard to the mass use of synthetic dyes such as anthraquinone, which are persistent as well as toxic. These have posed considerable risks to both aquatic ecosystems and human beings, as portrayed by alarming episodes of pollution in various concerns of the world. One of the promising solutions would be through bioremediation processes, especially via microorganisms such as *Candida tropicalis*. These yeasts have demonstrated incredible potential in the degradation of anthraquinone dyes through both photodynamic and enzymatic mechanisms. It converts harmful compounds into safer, less toxic forms. However, the successful application of bioremediation on a large-scale faces' challenges such as nutrient availability and environmental fluctuations. Future research should aim at improving growth conditions, utilizing biosurfactants, and investigating genetic engineering strategies to overcome these challenges. Enhancing the practical use of *C. tropicalis* and other bioremediation agents could lead to a more sustainable textile industry, reducing environmental impact and safeguarding aquatic life and human health.

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