Journal of Applied Science and Education, 2025,
Vol. 05, Iss. 01, S. No. 090, pp. 1-6
ISSN (Online): 2583-1372

Novel Techniques for Removal of Dyes from Wastewater: A Review

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How to cite this paper: P. Jangid, and M. P. Inbaraj, "Novel Techniques for Removal of Dyes from Wastewater: A Review," *Journal of Applied Science and Education (JASE)*, Vol. 05, Iss. 01, S. No. 090, pp 1-6, 2025.

https://doi.org/10.54060/a2zjournals.jase.90

Received: 19/01/2025
Accepted: 28/01/2025
Online First: 20/04/2025
Published: 25/04/2025

Abstract

Dyes are extensively used to color products across various industries, including textiles, leather tanning, cosmetics, and pigments. The textile sector alone accounts for approximately 14% of India's total industrial production, contributing around 4% to the nation's GDP and generating about 27% of its total foreign exchange earnings. However, the discharge of effluents from these industries poses significant environmental and health risks. In India, textile industries consume over 100 liters of water to process just 1 kg of textiles, which has led to the contamination of surface and groundwater resources in several regions. To mitigate the detrimental impact of dye-laden wastewater on human health and ecosystems, effective treatment is essential before effluents are discharged into water bodies. Consequently, the removal of dyes from wastewater has gained considerable attention in recent years due to the harmful, often carcinogenic, effects of untreated textile effluents. Dye removal from wastewater can be accomplished using a range of physicochemical or biological methods. This paper reviews existing literature on the importance of remediation technologies aimed at efficiently removing textile dyes from industrial effluents, with a focus on improving fragile ecosystems worldwide.

Keywords

Detoxification, Effluents, Remediation, Detrimental

1. Introduction

Water is an essential resource, indispensable for life and vital for sustaining all living organisms. Despite covering 71% of the Earth's surface, water is primarily salty, with about 97.5% of it being seawater and only 2.5% freshwater. Of this small fraction, just 0.007% is accessible for drinking. Dyes are widely used across various industries and when dyes enter water bodies, they cause visible discoloration, which becomes a public concern. These dye molecules also block sunlight from penetrating the water, which reduces the dissolved oxygen (DO) levels and affects the aquatic ecosystem. The textile industry is the largest contributor to dye. While the exact volume of dye effluents from each industry is not fully known, it is clear that the amount is substantial, contributing to a significant environmental issue [1]. Many methods for eliminating colors from water and industrial effluents have been developed in an effort to lessen these negative impacts. A combination of physical, chemical, and biological methods can be used to remove dye from wastewater. Commonly used techniques include adsorption, electrochemical treatment, membrane filtration, photochemical degradation, ion exchange, coagulation-flocculation, and biological treatment. Each method has its advantages and limitations, and no single technology is universally effective for all types of dye-contaminated wastewater. The choice of treatment method depends on factors such as the nature of the dye, the impurities in the wastewater, and the overall composition of the effluent. Dyes are typically categorized as anionic, cationic, or non-ionic, each with distinct chemical properties [2]. This review article provides a comprehensive summary of the various techniques used to remove dyes from water and wastewater, drawing from the latest literature. The primary aim is to present an up-to-date overview of the methods employed to address the growing challenge of dye contamination in industrial effluents.

2. Techniques for Dye Removal

Currently, the primary focus is on developing cost-effective and efficient methods for te treatment of wastewater. To achieve this, a range of treatment approaches, including physico-chemical, biochemical are being explored as efficient solutions for eliminating pollutants from textile industry wastewater [3].

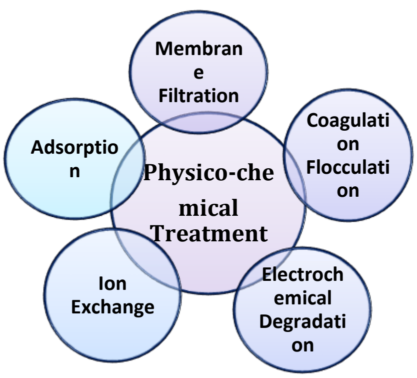

Figure 1. Physico-chemical Treatment

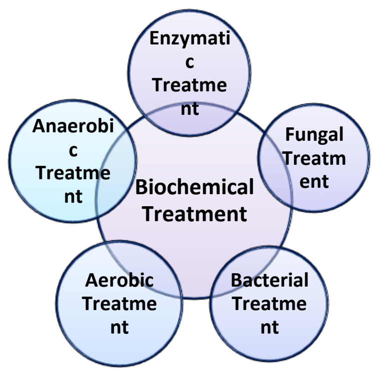

Figure 2. Biochemical Treatment

3. Physico-chemical Treatment

Practical In and commercial applications, wastewater is typically treated using physical or chemical processes. Physicochemical techniques for wastewater treatment include membrane filtration, coagulation/flocculation, ion exchange, electrochemical degradation, adsorption etc [4]. Some techniques are discussed-

Membrane filtration is a sophisticated purification and concentration treatment technique. By this method color, BOD, and COD can be removed effectively from wastewater. The fundamental principle of this technology relies on membrane pore size, which determines whether particles pass through or are retained at the barrier. Solutes larger than the pore size are trapped, resulting in a filtered solution free of these substances. Nano-membrane filtration offers advantages such as quick processing, minimal space requirements, and the ability to separate and reuse concentrated compounds, including non-reactive dyes. Ultrafiltration, operating at lower pressure than nanofiltration, provides a more economical solution with pore size ranging from 0.1 to 0.001microns [5].

The coagulation and flocculation are essential procedures in wastewater and drinking water treatment facilities. By decreasing the surface charge of scattered solid particles in water, these processes destabilize them and cause them to aggregate into bigger particles. Three different steps i.e. flash mixing followed by coagulation and finally flocculation make up the process. Traditional coagulation/flocculation using inorganic chemicals has notable drawbacks, including the generation of substantial volumes of useless or potentially toxic sludge. This sludge must either be incinerated or disposed of, leading to high costs and environmental concerns. However, recent developments in organic polymers have shown promising results as dye coagulants. These polymers not only demonstrate high effectiveness but also produce significantly less sludge compared to their inorganic counterparts, offering a more environmentally sustainable solution [6].

Electrochemical methods have gained significant attention in recent years due to their ability to achieve complete decolonization, operate within a moderate pH range, and require low final temperatures. In electrochemical processes, organic and toxic pollutants are eliminated through oxidation which may be either direct or indirect. In direct anodic oxidation, surface of anode adsorb the pollutants first then process the elimination via anodic transfer reaction. Strong oxidants are generated in indirect oxidation during electrolysis, and these oxidants then destroy the pollutants in the solution. These electrochemical techniques are environmentally friendly, as they rely solely on electron transfer for the oxidation process [7].

The physical process of adsorption has become a popular technique for removing dyes because of its exceptional capacity to get rid of nearly any kind of dyestuff. Adsorption occurs when components interact between two phases [8]. Adsorption is a mass transfer process. An effluent's content of dissolved particles is decreased by this method. Adsorption is a remarkable color removal method due to its ease of use and lack of particular equipment requirements. Moreover, starting the adsorption process doesn't require any pretreatment. Adsorption with activated carbon, nanoparticulate adsorbents, inexpensive adsorbents, and other adsorbent forms is frequently used to remove colors from water and wastewater [9].

Table 1. Dye Removal using Different Physico-Chemical Treatment

S.No.	Technique	Dye	% Removal	Reference
1.	Membrane Filtration i) Nanofiltration ii) Ultrafiltration	 Reactive Black 5 Reactive Black 5	 99 70	 10 11
2.	Coagulation-Flocculation Aluminium sulphate	Acid red 398	97.8	12
3.	Electrochemical Degradation Aluminium anode	Reactive red 43	99	13
4.	Adsorption Bio adsorbent	Remazol Brilliant Blue R	88.5	14

4. Biochemical Treatment

Since biological process may completely mineralize organic contaminants at a minimal cost, they are often considered to be environmentally favorable. Under certain climatic conditions, it is well known that a variety of microorganisms, such as bacteria, yeasts, fungus, and algae, can completely mineralize and decolorize a wide range of azo dyes [15]. Some biochemical methods are discussed.

4.1. Aerobic and Anaerobic Treatment

Aerobic treatment uses microorganisms to break down organic components in wastewater by using dissolved oxygen. An important characteristic of commercial dyes is their resistance to fading brought on by chemical and photo-oxidation, therefore dyes are typically resistant to oxidative biodegradation. The primary enzyme responsible for catalyzing dye degradation in aerobic environments is azo-reductase. The pace at which intermediate complexes are formed, temperature, dye concentration, and enzyme concentration are all important factors in the reduction of azo-dyes. The breakdown of azo dyes is known to create aromatic amines as intermediate metabolites, which are then further broken down by aerobic microbes to complete the mineralization of the azo dye [16].

Anaerobic dye degradation in wastewater is a promising technology that provides azo-dyes with a nonspecific and reasonably easy reduction process. Organic substances undergo this process, which produces carbon dioxide and methane without the presence of free oxygen. Azo dye reduction is catalyzed by non-specific azo-reductase bacteria during direct enzymatic catalysis. Nevertheless, there is currently no concrete confirmation of this enzyme's existence [17].

4.2. Bacterial Treatment

The capacity of bacteria to catabolize organic contaminants has been the subject of research in the context of bioremediation. Microorganisms, especially bacteria, are utilized as markers of different harmful compounds in wastewater and are essential in the remediation of organic pollutants. Compared to other microorganisms, bacteria are easy to cultivate and grow quickly, which is one of their key benefits. Additionally, molecular genetic manipulation can be used to increase the dye-degrading capacity of bacteria. Different bacterial species enable the biodegradation of azo dyes, which usually takes place in facultative anaerobic, aerobic, or anaerobic environments. Usually, azoreductase enzymes catalyze the reductive breaking of the azo link (–N=N–) to initiate the degradation process [18].

4.3. Fungal Treatment

Numerous reports have highlighted the ability of fungi to degrade a wide range of contaminants, such as organic waste, polycyclic aromatic hydrocarbons, dyes, and steroid chemicals. This ability is explained by the synthesis of a wide variety of extracellular and intracellular enzymes. As a potential substitute for the existing chemical and physical treatment techniques, fungal-based dye decolorization has been the subject of numerous investigations. Based on their specific features such as high biomass output, rapid growth, and vast hyphal networks, fungi are more successful than bacteria in several applications and are especially useful in bioremediation [19].

4.4. Enzymatic Treatment

The progressive breakdown and destruction of complex compounds is facilitated by the highly effective molecules known as enzymes. Enzymes and other biocatalysts are new technologies that are being used in many different industries because of their efficiency. Because of their reusability, non-toxicity, and environmental friendliness, they are very appealing for sustainable applications. When enzymes are used to adsorb dye molecules from wastewater, they are referred to as bioadsorbents or biosorbents. One effective method for addressing dye effluent issues involves the use of exoenzymes, such as peroxidases or phenol oxidases, which can degrade dye particles. Peroxidase enzymes, which are a type of hemoprotein, catalyze reactions like the adsorption of dye molecules from effluents in the presence of hydrogen peroxide [20].

Table 2. Dye Removal Using Different Biochemical Processes

S.No.	Treatment Process	Dye	% Removal	Reference
1.	Aerobic and anaerobic	Acid Orange 12 Disperse red 17	89 88	21
2.	Bacteria Aeromonas hydrophila Sphingomonas paucimobilis	 Crystal violet Methylene blue	 >90 85	 22 23
3.	Fungi Acremonium kiliense	 Malachite green	 95.4	 24
4.	Enzyme Soybean peroxidase	 Methyl orange	 81.4	 25

5. Conclusion

Water and human health are significantly impacted by dyes, a major class of contaminants. Wastewater must be properly treated before being released in order to lessen the negative effects that dye-contaminated water can have on people and the environment. The purpose of this study is to assess studies on different color removal strategies and procedures for wastewater from the textile sector. Both biological and physico-chemical approaches to treating wastewater containing dyes are highlighted in the literature that is currently available. Over 80% of dye is removed by many of these methods, and some even approach 90%. Significant progress has been achieved in recent years in the removal of dye from wastewater, with promising techniques that show remarkable dye removal efficiency in addition to being quick and affordable.

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