REVIEW ARTICLE

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Microbial Bioremediation Approaches for Textile Wastewater Treatment: Classification of Dyes and Their Environmental Impacts

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The discharge of dye-containing wastewater from the textile industry poses serious environmental and health risks due to the presence of toxic, recalcitrant compounds such as azo dyes, aromatic amines, and other synthetic chemicals. These pollutants are not only visually disruptive but also interfere with aquatic photosynthesis, bio-accumulate in organisms, and exhibit mutagenic and carcinogenic effects. Although conventional physicochemical methods—such as coagulation, flocculation, and oxidation—are employed for dye removal, they are often economically unfeasible, environmentally hazardous, and generate secondary pollutants. However, microbial efficiency can vary depending on the dye structure, the organism used, and the presence of inhibitory substances. Recent innovations include the use of microbial consortia, genetically engineered strains, and the incorporation of green-synthesized nanoparticles to enhance degradation performance. Furthermore, nano-bioremediation offers new prospects by integrating biological processes with advanced materials to address the breakdown of complex dye mixtures more effectively. This review presents an overview of dye types, their environmental impact, and the current microbial approaches employed in dye wastewater treatment. It also highlights key limitations and outlines emerging technologies and future research directions—of low-cost natural adsorbents—aimed at developing efficient and sustainable solutions for textile wastewater remediation.

Keywords: Dyes, Toxic compounds, Bio-accumulation, Textile, Treatment

INTRODUCTION

About 71% of Earth's surface consists of water, without which human survival is impossible. Yet, only around 2.5% of this is freshwater, while the vast majority—about 97.5%—is saline water locked in seas and oceans (1). Despite water's critical role, the textile industry has become notorious as one of the largest industrial polluters worldwide. At the same time, it remains one of the oldest and economically vital manufacturing sectors, employing nearly 35 million people and making a significant contribution to national economies (2).

Within textile production, wet processing steps such as desizing, bleaching, dyeing, and finishing are especially water- and chemical-intensive, involving salts, surfactants, alkalis, pigments, and dyes (3). A single textile mill producing 8,000 kg of fabric per day may consume about 1.6 million litres of water, with dyeing and printing alone accounting for nearly 24% of this use (4). Globally, the textile sector consumes around 700,000 tonnes of dyes annually, with an estimated 280,000 tonnes discharged into wastewater due to low fixation rates (5). Alarmingly, nearly 80% of this dye-laden wastewater is released untreated, posing severe threats to both aquatic ecosystems and public health (6).

The complex composition of textile effluents—including synthetic dyes, salts, heavy metals, and toxic organic compounds—makes them particularly challenging to treat (7). These pollutants persist in soils and waterways, disrupt photosynthesis, reduce oxygen levels, and exert mutagenic and carcinogenic effects (8). Their chemical stability and water solubility also render conventional treatment methods inefficient, often leaving behind harmful by-products (9).

In response, increasing attention has been directed toward microbial bioremediation as an eco-friendly and cost-effective alternative. Many bacteria, fungi, and algae possess the enzymatic capacity to degrade, transform, or immobilize dyes and associated pollutants (10). Unlike conventional treatments, microbial approaches can simultaneously remove color and detoxify harmful compounds, offering a sustainable solution to one of the textile industry's most pressing environmental challenges (11).

In the past few decades, the environmental impact of the textile dye industry has worsened. This trend is fueled by outdated production methods, ongoing use of harmful chemicals, gaps in worker training, poor hygiene practices, logistical inefficiencies, and inadequate disposal of dye-contaminated wastewater (12). As a result, untreated effluents remain a pressing environmental issue in many regions, posing significant threats to aquatic ecosystems and public health.

Given all this, there is an urgent need to develop treatment strategies that are both cost-effective and environmentally sustainable. Such methods should

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reliably clean dye-containing wastewater before it is released into natural water systems. In this context, the present review sets out to explore in depth the negative impacts of textile dye wastewater on the environment and living organisms, while also examining current and next-generation treatment technologies aimed at reducing harm and improving water safety.

Classification of dyes: Textile industries produce fibers to form yarn, which is converted to fabric (13). They use dyes in different ways on textile fabric. For instance, dyeing is the process of coating the textile fiber with dyes uniformly. Printing is the application of dyes to a specific area of the fabric. Bleaching is the removal of dye color (decolorization) from textile fibers, and finishing comprises crosslinking, softening, and waterproofing (14). Dyes are classified depending on their origin into two main categories. Natural dyes, which have been known ever since ancient times, are derived mainly from plants, and synthetic dyes are artificially synthesized from chemical compounds. Synthetic dyes are divided into three groups based on the nature of the manufactured fiber. These are cellulose fiber dyes, protein fiber dyes, and synthetic fiber dyes (15).

Cellulose Fiber Dyes: Cellulose fiber originates from plants such as linen, cotton, ramie, rayon, lyocell, and hemp. These types of fabrics give perfect dyeing results with reactive dyes, direct dyes, indigo dyes, and sulfur dyes (16).

Reactive Dyes: Reactive dyes constitute the major class of cellulose fiber dyes and work well with some protein fibers. They are known for their high pigmentation, permanent effect, facility of manipulation under a wide temperature range, and versatility due to diverse reactive groups able to form covalent bonds with multiple fibers (17). The chemical structure is shown in Figure 1.

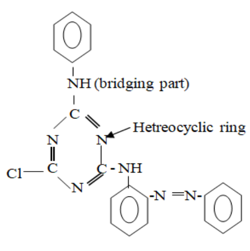
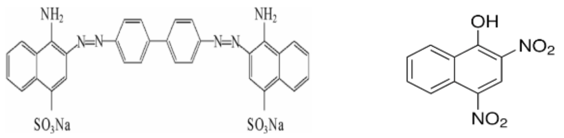


Figure 1: Chemical structure of reactive dyes (18).

Direct Dyes: Direct dyes are very affordable yet tend to remain in an aqueous form rather than binding to cellulose fibers (they can be used with certain synthetic fibers as well). Thereby, they are combined with inorganic electrolytes and anionic salts in the form of sodium sulfate (Na_2SO_4) or sodium chloride (NaCl) to enhance their fabric binding capacities. Thus, it is recommended to wash them in a cold cycle and with fabrics of the same color (14). Examples of direct dyes are given in Figure 2.



Congo Red Martius Yellow

Figure 2: Chemical structure of direct dyes (19).

Indigo Dyes: The indigo or dark blue color belongs to the classification of vat dyes, which are originally not soluble in water but become soluble after an alkaline reduction. The textile dyeing process occurs with the water-soluble or leuco form of indigo, then this form oxidizes under air exposure and returns to its original insoluble or keto form to ensure a perfect bonding of the dye to the fabric. Figure 3 shows the chemical structure of indigo dye. The indigo dyes are mostly used in blue denim dyeing, which explains their production in huge amounts around the world (20).

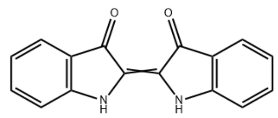


Figure 3: Chemical structure of indigo dyes (20).

Sulfur Dyes: Sulfur dyes constitute a small, yet important class due to their excellent dyeing properties, ease of application, and low cost. They have a complex structure with a disulfide (S–S) bridge. They belong to the vat dye classification; thus, they are reduced from the keto to the leuco form via sodium sulfide utilization. The chemical structure is shown in Figure 4. Leuco sulfur becomes soluble in water to achieve the dyeing purpose (14).

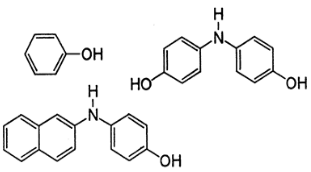
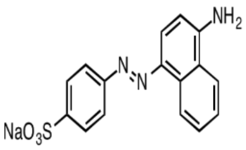


Figure 4: Chemical structure of Leuco Sulfur Black 11 (14).

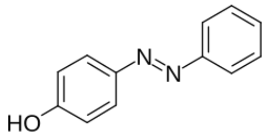
Protein Fiber Dyes: Protein fibers such as silk, cashmere, angora, mohair, and wool originate from animal sources. They are susceptible to high pH levels; hence, they are dyed using a water-soluble acid dye to obtain a molecule of an insoluble dye on the fiber. Acid dyes encompass azo dyes as the most important group, followed by anthraquinone, triarylmethane, and phthalocyanine dyes (21).

Azo Dyes: Azo dyes account for the largest category (60–70%) of the total synthetic dyes industry due to their versatility, cost-effectiveness, simplicity of utilization, high stability, and high intensity of the color (14). This dye has a prominent chromophore (-N = N-) structure

(Figure 5), ensuring the solubility of the dyes in water and their attachment to the fiber (14). Azo dyes are classified into three groups (mono, di, and poly) depending on the number of azo groups in their structure. These groups are attached to an aromatic or heterocyclic compound on one side and an unsaturated heterocycle, carboxyl, sulphonyl, or aliphatic group on the other side. Azorubine, Solvent Yellow seven are two examples of azo dyes.



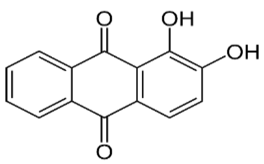
Azorubine



Solvent yellow seven

Figure 5: Chemical structure of Indigo dyes (14).

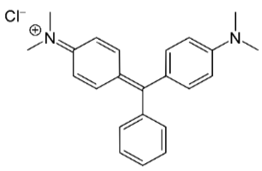
Anthraquinone Dyes: The class of anthraquinone is extensively used in textile dyeing industries; the red dyestuff, particularly, has been used for a long time (22). These dyes are known for their solubility in water, bright colors, and excellent fastness properties. The anthraquinone structure could constitute junctions with azo dyes (23). Alizarin is an example of anthraquinone dyes (Figure 6).



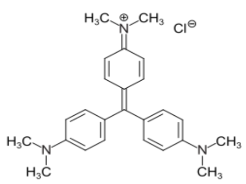
Alizarin

Figure 6: Chemical Structure of Anthraquinone Dyes (14).

Triarylmethane Dyes: The triphenylmethane dyes are widely applied in the textile industry for either dyeing wool and silk protein fibers, when formed of two groups of sulfonic acid (SO_3H). They can be used as indicators if they contain only one sulfonic acid (SO_3H) auxochrome in their chemical structure. These dyestuffs are known for their solubility in water and their wide and intense color range (14). Examples are given in Figure 7.



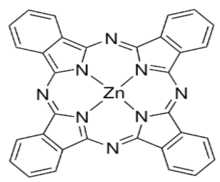
Malachite Green



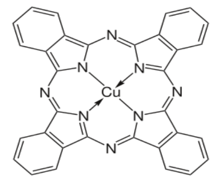
Crystal violet

Figure 7: Chemical Structure of Anthraquinone Dyes (14).

Phthalocyanine Dyes: The phthalocyanine family of dyes is synthesized by a reaction between the 1,4-dicyanobenzene compound with a metallic atom (Nickel, Cobalt, Copper, etc.) to produce green and blue shades. They have multiple inherent properties such as good colorfastness to light, resistance to oxidation, solubility in water, and chemical stability (25). Zinc phthalocyanine and copper phthalocyanine (Figure 8) are under this group.



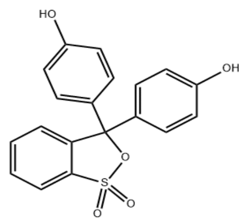
Zinc phthalocyanine



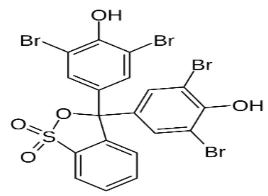
Copper phthalocyanine

Figure 8: Chemical Structure of Phthalocyanine Dyes (14).

Synthetic Fiber Dyes: Synthesized fibers are composed of spandex, polyester, acrylic, polyamide, polyacetate, polypropylene, ingeo, and acetate fabrics. They are used in 60% of global fiber production due to their wide application range. These fibers are dyed using direct dyes, basic dyes, and disperse dyes (25). Examples are given in Figure 9.



Phenol Red



Bromophenol blue

Figure 9: Chemical Structure of Synthetic Fiber Dyes (14).

Disperse Dyes: Disperse dyes are the smallest molecules among all dyes. These dyes are insoluble in water but stable under high-temperature exposure. The high-temperature dyeing solution is a mixture of the dyestuff powder and the dispersing agent (26). An example of a disperse dye is shown in Figure 10 below.

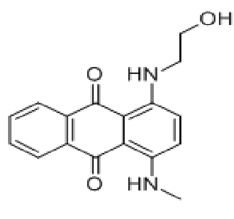


Figure 10: Chemical Structure of Disperse Blue 3 (14).

Basic Dyes: Basic dyes are also called cationic dyes because they transform into colorful cationic salts responsible for dyeing the anionic fiber textile (49). These dyes are susceptible to light; thus, they are strictly used for dyeing paper, nylon, and modified polyesters. Their principal structures are cyanine, triarylmethane, anthraquinone, diarylmethane, diazahemicyanine, oxazine, hemicyanine, and thiazine (23). An example of a basic dye is given in Figure 11 below.

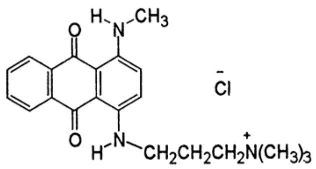


Figure 11: Chemical Structure of Basic Blue 22 (14).

Dyes and their effect

Animal exposure: Textile dyes' impact on the health of various groups of organisms, spanning from the simplest life forms to complex beings, such as mammals. The effects result in toxicity, bioaccumulation, changes in behavior, ecotoxicity, and mutagenic effects (28). Toxicity can lead to organ harm, reproductive issues, and, in some cases, cancer. Bioaccumulation impacts the whole food chain, influencing predators that consume contaminated species. Certain dyes might affect the nervous system, leading to alterations in behavior and reduced survival rates (29). Ecotoxicity affects ecosystems, impacting the development and reproduction of plants and microorganisms. The mutagenic and carcinogenic properties of these dyes pose serious health threats to animals exposed for extended periods. Recognizing the possible health hazards associated with exposure to textile dyes is crucial (29). Some azo dyes result in partially or completely degraded substances, including aromatic amines, which are deemed toxic and carcinogenic, negatively impacting the digestive systems of animals (29).

Aquatic animal health: The primary issue with textile wastewater is its color, resulting from the extensive use of synthetic organic dyes (30). When introduced to aquatic environments, dyes can experience transformation processes such as photodegradation, hydrolysis, and microbiological degradation. Dyes cause various environmental risks due to their strong thermal and photo stability, which hinders biodegradation and enhances persistence in the environment. The ability to absorb and reflect sunlight in dye-contaminated water reduces the photosynthetic efficiency of aquatic producers, thereby impacting the food chain. Additionally, elevated levels of textile dyes in water bodies obstruct the oxygenation capacity of the water, subsequently impeding biological processes in aquatic ecosystems (31).

Fish exhibit high sensitivity and responsiveness to alterations in their aquatic environment, with any negative changes potentially impacting the biochemical, physiological and histological aspects of fish. The toxicity from textile effluents threatens fish populations, both directly and indirectly, due to the direct buildup of contaminants. Toxic heavy metals and aromatic compounds in the dye are harmful to fish. These toxins can build up in fish tissues over time, leading to bioaccumulation. This process can lead to long-term health issues, such as organ impairment and weakened reproductive capabilities. Disruption of the food chain occurs when fish ingest water or prey contaminated with dye, affecting fish populations and their predators, such as bird species and humans. Dye contamination can lower oxygen concentrations in water bodies, leading to increased gill activity and reduced swimming behavior. It could also hinder the accessibility and visibility of prey, leading to reduced feeding efficiency and slower growth rates (32). The existence of dyes in water ecosystems can disturb the entire food web, affecting phytoplankton, zooplankton, and fish that rely on these organisms for nutrition. Dye contamination can build up in sediments, leading to habitat degradation, particularly for benthic fish populations (33). Altered habitats experience effects from the dark hue of wastewater, blocking light penetration, disturbing aquatic plants, and reducing the availability of refuge and spawning areas for fish. The combined effects of dye pollution could lead to reduced biodiversity in aquatic ecosystems, potentially resulting in the local extinction of vulnerable species and a rise in more resilient species, which in turn reduces ecosystem resilience and function (34). Contact with certain dyes can interfere with growth hormones, leading to impaired development.

Larger fish might accumulate greater amounts of dyes in their bodies, possibly attaining lethal concentrations. Certain dyes might disrupt reproductive processes, leading to lower fertility or birth defects in offspring. Several studies show that textile wastewater has negative impacts on fish, as seen by zebrafish exposed to reactive colors, which exhibited lower survival rates as well as DNA damage and oxidative stress (35). When exposed to effluent containing azo dyes, tilapia displayed gill damage, metabolic abnormalities, and aberrant behavior. The study found that fish tissues bioaccumulate heavy metals found in textile wastewater, resulting in persistent toxicity (36).

Adult fish exposed to reactive azo dyes may experience DNA damage, which can lead to cell abnormalities. Studies on *Catla catla,* a freshwater fish, subjected to Reactive Red 120 showed significant damage to gill and blood cells, including micronuclei, nuclear buds, and fragmented apoptotic cells, indicating a distinct genotoxic effect (37). The negative effects of wastewater containing dye on fish include alterations in the form and size of red blood cells, DNA damage, and cellular damage (38).

Impacts of dye on phytoplankton: Phytoplankton, which are essential to aquatic ecosystems, are seriously threatened by dye pollution. Light penetration is reduced by the presence of colors in bodies of water, which raises turbidity and thus restricts photosynthesis, which is essential for the development and survival of phytoplankton. Toxic compounds found in many synthetic dyes interfere with phytoplankton cells' functions, which hinders their growth (39). In addition, dangerous compounds such as heavy metals (Cu, Zn, Pb, etc.), aromatic amines, crystal violet, malachite green, phthalocyanine blue, etc., found in dyes can build up in phytoplankton and move up the food chain, perhaps harming species at higher trophic levels (39). In addition to its direct toxicity, dye contamination can change the availability of nutrients, resulting in imbalances that affect the output of phytoplankton and alter community composition. Eutrophication can result from the addition of nutrients from dyes, which can cause oxygen depletion and harm aquatic life. Under polluted conditions, some phytoplankton species may gain a competitive advantage, which can lead to a decline in species variety and disruption of ecological equilibrium. These alterations have the potential to interfere with the normal sequence of phytoplankton blooms, altering their seasonal patterns and community interactions (40). Dye pollution can have cumulative consequences that spread throughout aquatic environments, reducing water quality, changing food webs, and impairing the functioning of the ecosystem. To reduce these risks and safeguard phytoplankton populations, effective wastewater treatment and pollution control strategies are necessary. Moreover, textile-derived microfibers and colored fiber particles endanger phytoplankton in addition to chemical pollutants. These fibers, often mistaken for food by zooplankton, disrupt the aquatic food web. They lessen the amount of light available to phytoplankton in deeper strata and sediments because they are suspended in the water column. Modified fiber fragments—such as those dyed or treated for water repellency—can serve as carriers for persistent, bioaccumulative, and toxic substances, thereby playing a role in the spread of invasive species (41).

Human exposure explores: Textile dyes are known to be highly toxic and potentially carcinogenic, and their use has been associated with a range of health issues in both humans and animals (42). These dyes can trigger conditions such as dermatitis and even affect the central nervous system. Such harmful effects may result from the displacement of enzyme cofactors, leading to enzyme deactivation (43). When dyes are ingested or inhaled, particularly in dusty environments, they can irritate the skin and eyes (44). Workers exposed to reactive dyes are especially vulnerable to allergic conditions, including contact dermatitis, allergic conjunctivitis, nasal inflammation (rhinitis), and work-related asthma (45). These allergic responses involve the formation of Immunoglobulin E (IgE) antibodies, which are stimulated when reactive dyes bind to human serum albumin and function as antigens (46).

The textile industry frequently encounters hazardous substances, some of which can disrupt reproductive functions like ovulation and sperm production. Azo dyes, especially those derived from benzidine, are widely used in textiles, paper, and leather manufacturing. They have been extensively studied due to their toxicity and have been linked to bladder cancer in humans. In mammals, these dyes are broken down by gut bacteria into aromatic amines—compounds known for their carcinogenic potential (47).

Dyes like Reactive Green 19, Disperse Red 1, and Reactive Blue 2 have shown long-term genotoxic effects. Reactive Green 19 exhibits dose-dependent genotoxicity, while the other two dyes have also demonstrated potential health risks. When textile dyes and heavy metals enter water bodies, aquatic organisms like fish absorb these contaminants, which then accumulate in human tissues through the food chain. These compounds, often carcinogenic, can reach concentrations in the human body that are 1,000 times higher than their original levels in water. Prolonged exposure may result in serious conditions such as bladder, colon, and colorectal cancers, as well as skin irritation and respiratory symptoms like coughing, sneezing, and wheezing (48)

Some dyes, particularly azo-based ones, also possess mutagenic properties. For instance, Sudan I—a fat-soluble azo dye used in textiles and food—can be enzymatically broken down by intestinal microbes into carcinogenic amines. Both the dye and its byproducts carry cancer risks. Azure B, a key metabolite of Methylene Blue and a cationic dye, can insert itself into DNA and RNA helices (49). It may also lodge in animal cell membranes and disrupt enzyme function. Notably, it acts as a reversible inhibitor of monoamine oxidase A—an important enzyme in the human brain—potentially influencing behavior (50). Azure B also inhibits glutathione reductase, an enzyme critical to maintaining cellular redox balance. Triphenylmethane dyes like Basic Red 9, commonly used in the textile, paper, leather, and ink industries, are also considered carcinogenic because they release aromatic amines during anaerobic breakdown. Similarly, Crystal Violet can cause bladder inflammation, skin and gastrointestinal irritation, and may lead to respiratory and kidney failure (51). Alarmingly, over 100 of the 4,000 dyes that have been tested as toxic are still commercially available, despite existing bans, continuing to pose serious health risks due to their ability to form carcinogenic amines (52). In Figure 1, it is very clear how dye-laden wastewater has harmful impacts on the human body. It causes various organ-specific diseases as well as weakens various systems of the human body. The carcinogenic effects of these dyes can lead to death (53).

Current methods for textiles' wastewater treatment

Oxidation method: Oxidation-based dye degradation technologies are generally classified into two categories: chemical oxidation and advanced oxidation processes (AOPs**)**. These methods are capable of partially or completely breaking down toxic compounds, including dyes and pesticides, under normal environmental conditions. AOPs are specifically designed to generate high concentrations of hydroxyl radicals (OH), highly reactive species known for their strong oxidizing capacity. These radicals are effective in degrading complex and harmful chemicals present in wastewater (54).

In contrast, chemical oxidation relies on agents such as ozone (O_3) and hydrogen peroxide (H_2O_2). At high pH levels, these oxidants produce non-selective hydroxyl radicals that can attack the conjugated double bonds in dye chromophores as well as complex aromatic structures, effectively breaking them down. This results in smaller, non-colored molecules, leading to reduced coloration in effluents (55). These techniques are particularly effective against dyes with double bonds. However, the efficiency of chemical oxidation is generally lower than AOPs due to reduced hydroxyl radical generation (56). A significant advantage of ozonation is that ozone can be applied in its gaseous form, which does not increase wastewater volume or produce sludge. Yet, one major limitation is that ozonation can lead to the formation of toxic byproducts, even from otherwise biodegradable dyes (57).

Advanced oxidation, a more aggressive approach, is based on the *in-situ* production of hydroxyl radicals to treat dye-containing wastewater. Common AOP methods include photocatalysis, Fenton reactions, photo Fenton processes, ozonation, and electrochemical oxidation. These methods are efficient under extreme conditions and can quickly eliminate dyes without generating sludge. Nonetheless, drawbacks include high operational costs, sensitivity to pH, and the potential creation of harmful byproducts (58). Photocatalysis has been extensively researched for the treatment of textile wastewater (59). It involves using nanoparticles such as zinc oxide (ZnO) and titanium dioxide (TiO_2), which act as catalysts to generate both free radicals and electron holes. The holes contribute to the oxidation of dye molecules, producing OH• radicals and mineralization products, while electrons reduce oxygen to superoxide radicals (60). Among AOPs, Fenton and photo-Fenton processes are some of the most used for breaking down organic pollutants like dyes. These methods employ a mixture of hydrogen peroxide and ferrous iron (Fe^{2+}) (61). The Fenton reaction begins with the production of hydroxyl radicals (Eq 1), which is further enhanced in the presence of light in the photo-Fenton process (Eq 2& 3). Similarly, ozonation contributes to OH• radical formation (61) through a sequence of initiation (Eq. 4), propagation (Eqs. 5 & 6), and termination steps (Eqs. 7 & 8).

$$Fe^{2+} + H_2O_2 \rightarrow OH\bullet + Fe^{3+} + OH^- \quad (1)$$
$$UV + H_2O_2 \rightarrow 2OH\bullet \quad (2)$$
$$Fe^{3+} + UV + H_2O \rightarrow OH\bullet + Fe^{2+} + H^- \quad (3)$$
$$H_2O + O_3 + h\upsilon \rightarrow O_2 + 2OH\bullet \quad (4)$$
$$OH\bullet + O_3 \rightarrow O_2 + HO_2\bullet \quad (5)$$
$$HO_2\bullet + O_3 \rightarrow 2O_2 + OH\bullet \quad (6)$$
$$HO_2\bullet + OH\bullet \rightarrow O_2 + H_2O \quad (7)$$
$$2OH\bullet \rightarrow H_2O_2 \quad (8)$$

Physical method: Physical methods can also be employed to remove dispersion dyes and other pollutants from wastewater, although their use is somewhat limited. These techniques often suffer from low decolorization efficiency and tend to generate a significant amount of sludge (62). To make the adsorption method more economically feasible, researchers have explored the use of low-cost absorbents such as peat, bentonite clay, fly ash, and polymer resins. However, these materials face various limitations that hinder their widespread application. Therefore, adsorption is best suited for treating wastewater with low pollutant concentrations, or when the adsorbent is inexpensive or can be easily regenerated (63).

Ultrafiltration: One advanced physical treatment method **is** ultrafiltration (UF), which has become increasingly popular for its effectiveness in removing a broad spectrum of contaminants. UF is a membrane-based filtration process that uses hollow fiber membranes with very fine pores to separate water from suspended solids, colloids, and large molecules. In vacuum-driven UF systems, suction pulls water through the membrane pores into the fibers, producing clean filtration. In pressurized systems, water is forced through the membranes under pressure. Both types are highly efficient at eliminating particles, bacteria, viruses, and other impurities, making UF suitable for both drinking water and industrial applications (64).

Nanofiltration: Nanofiltration (NF) is another membrane technology similar in design and operation to reverse osmosis (RO) but differs in key aspects. NF membranes are less dense than RO membranes, requiring lower pressure and providing reduced removal of monovalent ions (e.g., sodium and chloride). However, they are very effective at removing dyes and trivalent ions (Cu^{2+}, $Pb^{2+,}$ $Fe^{3+,}$ etc.), making NF ideal for water softening (65) and treating water with low total dissolved solids (TDS). It is also effective in organic matter removal, although it is not always the most economical method (66).

Loose Nanofiltration: A recent development in membrane technology is Loose Nanofiltration (LNF). LNF membranes feature larger pores and higher permeability, allowing for better passage of both monovalent and multivalent salts, while still achieving strong rejection of organic molecules. They also function at lower operating pressures, improving energy efficiency. Research suggests that resveratrol-based LNF membranes have great potential for treating saline textile wastewater (66).

Sol-gel-assisted interfacial polymerization: An innovative membrane fabrication technique called sol-gel-assisted interfacial polymerization enables the simultaneous formation of titanium dioxide during membrane synthesis. This method improves the morphology and performance of NF membranes and imparts self-cleaning properties, making them more sustainable and efficient (68).

Reverse osmosis: Reverse osmosis (RO**)** is among the most effective water purification methods available. In RO systems, water is pressurized and forced through a semi-permeable membrane with pores small enough to allow only water molecules to pass, while salts, microbes, and other contaminants are retained. This produces high-purity water on one side and a concentrated waste stream on the other. RO can remove up to 99% of dissolved salts and impurities, making it ideal for both domestic and industrial water treatment. The performance of RO systems can be enhanced by adding post-filtration stages**,** such as carbon polishing filters, to capture any residual contaminants (69).

Physicochemical methods: Currently, the main objective concerning water pollution is to develop economic and efficient techniques for treating wastewater discharges from the textile sector to safeguard aquatic life in water bodies. The most prevalent physicochemical methods employed for treating textile wastewater include ion exchange, adsorption, coagulation and flocculation, filtration, and electrochemical methods. Coagulation and flocculation are effective in removing colors from disperse and sulfur dyes, although they exhibit limited effectiveness for chemical and vat dyes. Adsorption techniques have attracted significant attention due to their enhanced removal performance, which is attributed to high affinity, the capability to target specific compounds, and the preference for adsorbent regeneration. Below are some methods that have been recently reported and may be applicable for wastewater treatment (70).

Adsorption: Adsorption is a surface-based mechanism where molecules or ions are drawn to the surface of a solid adsorbent. There are two categories of adsorption: physisorption and chemisorption. This classification depends on how the dye molecule adheres to the adsorbent surface (71). During the adsorption of dye molecules, various forces such as van der Waals forces, hydrophobic and electrostatic interactions, and hydrogen bonding can be present (72). The principle of adsorption relies on adsorbents, which typically possess porous structures that enhance the total exposed surface area necessary for the rapid and effective adsorption of dye molecules from wastewater (73). Numerous adsorbents, including zeolites, alumina, silica gel, and activated carbon, have been extensively utilized for the removal of dyes from wastewater. Activated carbon is a widely used adsorbent on an industrial scale. The benefits of the adsorption process encompass the reusability of adsorbents, high efficiency, and a brief duration required for the removal of dyes from wastewater (74).

Ion exchange technique: The ion exchange technique has recently gained significant interest in treating textile wastewater and effluents due to its benefits, including affordability, regeneration potential, simplicity, adaptability, and high efficiency. Successful separation in the ion exchange technique is accomplished by forming strong connections are formed between the resins utilized in a packed bed reactor and the solutes (75). The process of ion exchange for dye elimination relies on the interactions between resin functional groups and the charges present on dye molecules (76).

Coagulation and flocculation: Wastewater typically holds a considerable level of contaminants and harmful substances. Consequently, it may be processed with coagulants before disposal. In this approach, metal salts and polymers act as coagulants, whereas flocculants are polymers that promote the clumping of flocs, making their separation easier (77). Coagulants are added during the intense mixing stage. The presence of coagulants neutralizes or reduces the charge of finely dispersed particles. In the end, flocculants join with fine particles to form larger particles that can be easily separated by sedimentation (78). In the coagulation-flocculation procedure, different chemical coagulants are also employed. Iron coagulants like ferric chloride, ferrous sulfate, and ferric chloride sulfate are usually introduced to maintain the removal system's purity, whereas other chemical coagulants, including magnesium carbonate and hydrated lime, are essential for adsorbing azo dyes and their derivatives (78, 79). When a coagulant is added to a solution and stirred forcefully, it forms a precipitate, trapping organic pollutants and impurities. The filtered substances can then be physically separated to produce treated clean water (80).

Electrochemical processes: Electrocoagulation, electro-Fenton, and anodic oxidation are three methods of electrochemical processes. Electrochemical treatment methods do not need chemical additives and generate no sludge. Nonetheless, the drawbacks of these methods consist of elevated energy expenses and being less efficient compared to alternative treatment technologies (81). The electrocoagulation method utilizes two metallic electrodes for direct energy provision and the generation of in-situ coagulant particles, along with the electrocoagulation process used to treat dye-containing wastewater (82). The iron anode functions as a catalyst and coagulant, whereas the cathode produces hydrogen gas. This approach is notable for producing minimal sludge, being cost-effective, user-friendly, and not needing chemicals (83). Anodic oxidation represents a different electrochemical method employed to eliminate organic contaminants from wastewater through direct or indirect processes (84). During the direct oxidation process, organic compounds are captured at the surface of the anode and subsequently broken down via the anodic electron transfer mechanism. Conversely, potent oxidizing agents like O_3 and H_2O_2 are generated electrochemically through the indirect oxidation method. This technique is notable for its effective elimination of dyes and various organic contaminants. Nonetheless, it presents various disadvantages, such as elevated operational expenses and poor stability (85).

Biological methods: The biological process eliminates solely the dissolved substances in textile wastewater. The efficiency of removal is affected by the ratio of organic load to dye, the number of microorganisms, temperature, and oxygen levels in the system. According to oxygen needs, biological methods can be categorized as aerobic, anaerobic, anoxic, facultative, or a mix of these. Biological techniques for the total degradation of textile wastewater offer several advantages, including: (a) environmentally friendly, (b) cost-effective, (c) reduced sludge generation, (d) producing non-toxic metabolites or achieving complete mineralization, and (e) decreased water usage (higher concentration or reduced dilution needs) when compared to physical/oxidation methods. The effectiveness of biological techniques for degradation relies on the suitability of the chosen microbes and the function of enzymes. A diverse array of microorganisms, like bacteria, fungi, and algae, can break down many types of dyes found in textile wastewater (86).

Fungal-assisted degradation of dye-containing wastewater: Fungi, via different fungal strains or groups, significantly contribute to the breakdown and mineralization of various textile dyes. The main benefit of utilizing fungi for treating dye-laden wastewater is the capacity to enhance their metabolism to reach ideal environmental conditions (86). Intracellular and extracellular enzymes, including manganese peroxidase, laccase, and lignin peroxidase, can enhance their metabolic processes (87) and assist in the treatment of wastewater that contains dyes. Since the early 1990s, the role of white-rot fungi in breaking down persistent organic pollutants, such as azo dyes, has been demonstrated because of their general lignin-modifying enzymes (88). Laccase, an enzyme produced by fungi, has proven effective in eliminating 70–88% of dye molecules, and in certain instances, has been used in combination with manganese peroxidase and lignin peroxidase to decompose dye molecules (89). Reports indicate that, based on the processing environment, fungi can generate various oxidative enzymes (90).

Algae-assisted degradation of dye-containing wastewater: Algae have attracted considerable attention as bio-coagulants for biodegrading textile dyes because of their favorable cell wall characteristics, extensive surface area, high binding capacity, and strong affinity (91). Under normal atmospheric conditions, bioprocesses using algae are usually easy to manage; they are also eco-friendly and more cost-effective compared to traditional treatment techniques (92). Moreover, in contrast to bacteria and fungi that need the introduction of carbon and other elements to eliminate dyes, algae do not require such additions. Algae can eliminate textile dyes by means of adsorption, enzymatic degradation, and the assimilative use of dye molecules. In adsorption processes, algae attach dye molecules to their cell surfaces through different interactions and efficiently eliminate them from wastewater. Algae can generate different enzymes that break down complex dye molecules into simpler, less toxic substances. Certain algae can use dye molecules as their source of carbon and nitrogen for growth, efficiently removing and metabolizing the dye (93).

Bacteria-assisted degradation of dye-containing wastewater: Table 1 summarizes various bacterial species and consortia used for dye degradation, highlighting the treated dye types, percentage of degradation achieved, operational conditions (pH, temperature, and time), and the key enzymes implicated as reported in previous studies.

Table 1: Bacterial bioremediation of textile dyes.

Bacterial Species / Consortium	Dye Treated	% Degradation	Conditions (pH, Temp, Time)	Enzymes Involved	References
Aeromonas hydrophila LZMG14	Malachite Green	≈96.8%	Unspecified, ~12h	Azoreductase	(94)
Bacillus stratosphericus SCA1007	Methyl Orange	90%	pH 7, 35°C, 12h	Likely azoreductase	(95)
B. thuringiensis strain F5	Methylene Blue	95%	35°C, 12h, 10g/L NaCl	Mn-peroxidase, laccase, LiP	(96)
Pseudomonas aeruginosa + *B. subtilis*	Allura Red R-40	88–92%	Microaerophilic, 264h	Azoreductase	(97)
Bacillus farraginis	Orange M2R	98%	pH 7, 37°C, 6d	Azoreductase	(98)
Bacillus sp. CH12	Reactive Red 239	100%	pH 10, 30°C, 24h	Azoreductase	(99)
Streptomyces albidoflavus 3MGH	RO 122, DB 15, DB 38	~60–61%	pH 6, 35°C, 5d	Laccase (5.96 U/mg)	(100)
Klebsiella pneumoniae	Methyl orange	83%	20 µM, pH 8, 40 ◦C, 10 min	20 µM, pH 8, 40 ◦C, 10 min	(101)
Shewanella sp.	Reactive Black-5, Direct Red-81, Acid Red-88	96.9	200 mg/L, pH 8.5, 35 ◦C, 12 h	Azoreductase	(102)
Alcaligenes sp. TEX S6	Direct Red 28	86	150 mg/L, pH 7, 37 ◦C, 48 h	Not identified	(103)
Actinomycetes strains	Orange dye	85	50 mg/L, pH 7.2, 37 ◦C, 48 h	Not identified	(104)

Microbial fuel cell-assisted degradation of dye-containing wastewater: In a microbial fuel cell (MFC) setup, specific electrochemically active microorganisms located in the anode chamber are essential for the treatment of textile wastewater. These microorganisms process and decompose a variety of organic contaminants found in wastewater via oxidation reactions. In this biochemical reaction, electrons and protons are produced as by-products. The electrons travel through an external circuit, producing an electrical current, while the protons move through a proton exchange membrane toward the cathode compartment. At the cathode, protons merge with the incoming electrons and molecular oxygen, eventually resulting in the conversion of oxygen into water. This combined system aids in wastewater treatment while also allowing for concurrent bioelectricity production (105).

Challenges, overcome, and future research: The textile industry consumes around 200 tons of water to produce just one ton of fabric, discharging this water as toxic waste containing hazardous pollutants like unbound dyes, aromatic amines, and other contaminants (106). These pollutants lead to serious environmental problems, including ecotoxicity, bioaccumulation in ecosystems, and disruptions in aquatic life due to reduced photosynthesis and eutrophication. A significant concern is the presence of 15–20% unbound dyes in untreated wastewater, which may also carry mutagenic and carcinogenic risks from azo dyes and their breakdown products (107).

While biological dye removal is seen as a safer and eco-friendly solution, its effectiveness varies. Microbial strains differ in their ability to decolorize the same dye, and even the same strain may respond differently to various dyes. Genetically modified microbes and immobilized enzymes have also shown limited success (86). Still, microbial remediation offers notable advantages such as rapid growth, extended retention, less toxic by-products, and lower sludge generation (108). However, challenges remain due to dye complexity, microbial resistance to inhibitors, and difficulty in adapting microbes to diverse effluents (108).

Using microbial consortia shows promise, as these are generally more robust and adaptable than single strains. Genome engineering of microbes could further optimize bioremediation (109). Microbial efficacy also depends on physiological features such as cell wall and membrane composition. Integrating Bio-electrochemical systems with microbial-enzyme processes can enhance resource recovery, minimize sludge, generate clean energy, and produce biomass (110).

Nanotechnology provides another promising avenue for dye treatment. Though nanoparticles (NPs) in trace amounts (μg/L) are generally safe, high concentrations (mg/L) can cause problems such as membrane blockage, water turbidity, and sludge accumulation, contributing to eutrophication (111). Despite their advantages, metal oxide nanomaterials face hurdles like eco-friendly synthesis, cost efficiency, and challenges in managing secondary waste (112). Biologically synthesized NPs are considered less toxic and more sustainable, but concerns remain about their reusability. Combining these green NPs with microbes or enzymes may enhance effectiveness and reduce environmental hazards (113).

Further research is essential to assess the long-term safety, reusability, and environmental impact of green nanomaterials in industrial applications. The purification of biogenic NPs and the development of advanced nanohybrids with multifunctional capabilities should also be prioritized. Cost analyses should compare green versus conventional synthesis methods (114).

'Omics' technologies such as metagenomics and metabolomics can provide deeper insight into enzymatic degradation pathways. However, complete dye breakdown remains difficult. More studies should focus on testing bacterial strains in real textile effluent instead of lab models, understanding microbial inhibitor effects, and addressing the fate of microbial isolates after degradation (114).

Fungi and yeasts, including their consortia, are emerging as potential cost-effective solutions due to their high degradation ability and capacity to produce valuable by-products like biodiesel. The use of immobilized enzyme systems (laccases, manganese peroxidase, LiP, and horseradish peroxidase) could help decolorize wastewater without generating toxic intermediates (115).

Further advancements are needed in the kinetic modeling of biological and chemical reactions, especially regarding the formation of intermediate compounds. Low-cost natural materials and waste-derived adsorbents should also be evaluated as substitutes for activated carbon in dye treatment. Additionally, future research must explore the role of layered double hydroxides (LDHs), hybrid catalysts, and metal-organic frameworks (MOFs) in electrochemical and advanced oxidation processes (AOPs) to enhance dye removal. Solar-powered MOFs for low-cost degradation of dyes are a key focus area, along with strategies for biochar recovery and reuse. Biogenic nanoparticles combined with microbes or enzymes continue to offer promise for safer and more sustainable textile dye remediation. (115).

CONCLUSIONS

The release of dyes into water sources poses significant threats to both human and animal health, emphasizing the urgent need for sustainable and cost-effective treatment strategies. One of the key challenges in managing textile industry wastewater is the effective bioremediation of these dyes. While numerous physical and chemical techniques have been explored, they often involve high costs and can negatively impact the environment. In comparison, biological treatment methods, especially those involving bacteria, offer a more sustainable, economical, and efficient alternative. Various studies have confirmed the ability of specific bacterial strains to break down and remove textile dyes. These microorganisms can play a vital role in the decolorization of dye-laden wastewater through mechanisms such as biodegradation and biosorption. Looking ahead, research should prioritize the discovery of novel extremophilic organisms and enzymes that can withstand industrial conditions and effectively break down synthetic dyes. The use of microbial consortia and natural ecosystems will further strengthen biotechnological approaches to wastewater treatment. Moreover, the development of green nanomaterials and advanced photocatalysts that minimize ecological toxicity and produce fewer harmful byproducts will be essential for large-scale industrial applications and environmental restoration.

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