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Biotechnological Approach to Treat Textile Dyeing Effluents: A Critical Review Analysing the Practical Applications

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Review

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ABSTRACT

Although the textile industry is one of the significant contributors to the global economy, approximately 10% of the annual global dye production, amounting to 7×10^6 tonnes and spanning a spectrum of 10,000 different dye variants, is wasted in the dyeing process and subsequently released into the environment. Following the dyeing and processing stages, this waste contributes to environmental pollution, making the textile industry account for 20% of the overall industrial water pollution worldwide. Traditional treatment of effluents is burdensome for the majority of textile units that are micro-scale enterprises. A significant challenge is that there isn't a single, commercially viable way to efficiently treat wastewater from textile industries. Scholars from several disciplines are working together to investigate novel approaches that are assiduously directed at addressing environmental issues by minimising waste, thereby promoting sustainability, circular economy, and industrial symbiosis. This study aims to address the challenges associated with the treatment process of textile dye-related effluents by conducting a comprehensive analysis of recent research on treatment processes and advancements and exploration of biotechnological treatment methods that are focused on achieving the reuse of treated water. The review covers different processes, traditional, current and emerging techniques, and it emphasises their use in practical situations. Also, the efficiency, specificity, and environmental friendliness of different biotechnological approaches are discussed offering a comparison of their benefits and drawbacks. A holistic remediation approach is advocated by harmonizing both conventional and non-conventional treatment methods for a more comprehensive solution.

KEYWORDS

textile dyeing effluents, biotechnological approach, wastewater, remediation, nanotechnology

INTRODUCTION

The textile industry is the second-largest employer in India, after agriculture, and one of the most important sectors of the country's economy [1]. The Latin word "texere" is the source of the English term "textile," which means to weave. The application of colour to textiles and fabrics is known as industrial textile dyeing, it is a sophisticated and crucial process in the textile industry. To make textiles aesthetically pleasing for a variety of purposes, including fashion, home furnishings, and technical textiles, this procedure is essential. One of India's oldest and biggest industrial sectors is the textile

industry, with a workforce of over 35 million and employment prospects, it is the second-largest industry in the nation. The textile market in India was valued at USD 108.5 billion in 2015, and by 2023, it is projected to grow to USD 226 billion [2]. It is in charge of 14% of India's overall industrial manufacturing. India has a 5% position in the global textile market, making it the second-largest manufacturer of textiles [3]. The worldwide textile sector is expected to grow to be worth USD 1002.84 billion by 2027, which coincides with an increase in water pollution brought on by textile dye-rich, large-volume effluents, underscoring the need for source clean-up [4]. Around 10% of the 7×10^6 tonnes of dyes of around 10,000 distinct dyes produced annually worldwide is wasted during the dyeing process and is subsequently discharged into the environment after dyeing and processing. According to the World Bank, the textile industry is responsible for 20% of global industrial water pollution. According to the U.S. Environmental Protection Agency, processing one kilogram of fabric requires 100-200 litres of water [5]. About 20% of the world's population no longer has access to clean water due to water body contamination, and 40% live in unhygienic conditions. In the past thirty years, governmental authorities, businesses, and society at large have grown more concerned about environmental issues related to biological and chemical contamination of water supplies [6]. Because of their detrimental impacts on the ecosystem, textile dyeing effluents, which are released from industrial facilities engaged in textile dyeing processes, pose serious environmental issues. These effluents are extremely harmful to both terrestrial and aquatic life because they contain a complex mixture of chemicals, heavy metals, artificial colours, and other pollutants. Despite the existence of mandatory regulations regarding the compliance of treatment standards for industrial effluents, water pollution due to textile dye units appears to be on the rise [7].

The goal of ongoing research is to identify challenges in the treatment of textile dye industry effluent and establish environmentally acceptable ways to handle these effluents to protect the ecosystem from their harmful impacts. This review-based article summarizes the current trends and existing knowledge about the remediation process available and investigates the sustainable approach to deal with the aforementioned issues. The authors reviewed the related literature and concluded the potential approach of treatments with environment-friendly and economical visibility; along with discussions on prospects in this area.

In the textile dye effluent treatment, conventional methods have long taken the spotlight in research. Countless studies have outlined their advantages and disadvantages. However, in this exploration, this research functions as a critique of biotechnological processes for treating textile dye effluent. Yet, rather than stopping at mere critique, our work goes beyond and advocates for a synergistic remediation approach in treating textile dye effluent. This approach integrates both conventional and non-conventional treatment processes to offer a comprehensive solution.

TEXTILE DYEING PROCESS AND EFFLUENT COMPOSITION

Industrial textile dyeing is a broad field that includes both contemporary and classic dyeing procedures, such as continuous and batch dyeing. To achieve the best colour absorption and fastness, textile materials are treated with particular dye formulations in controlled pH, pressure, and temperature environments. Through dyeing, textiles gain aesthetic appeal and become ideal for a range of uses in fashion, home furnishings, and technical fabrics. There are several methods for dyeing textiles, all aimed at producing certain colour effects and patterns. The two most popular techniques are continuous dyeing, which is appropriate for large-scale production and includes continuously moving fabrics through dyeing machinery, and batch dyeing, which involves dyeing a certain quantity of textiles in a closed vessel. Based on their chemical compositions and techniques of application, dyes used in textile dyeing can be divided into several groups, such as direct dyes, reactive dyes, vat dyes, disperse dyes etc. Preparation, dyeing, rinsing, and finishing are some of the steps that are usually included in the process. To achieve consistent and vivid colouration, each of these steps requires careful control over variables including temperature, pH, dye concentration, and agitation [8,9]. Figure 1 shows effluent discharge from textile plants during all steps of fabric production and dyeing.

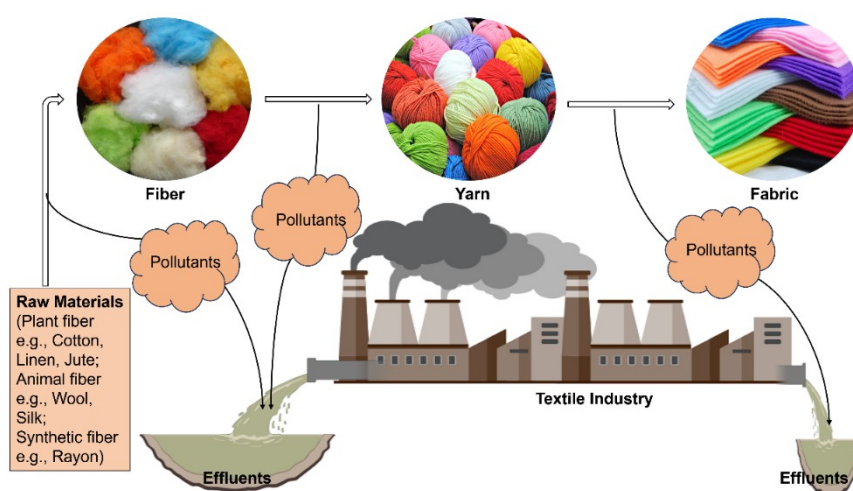


Figure 1. Production of effluent water from the textile industry

ENVIRONMENT & HEALTH IMPACT OF TEXTILE EFFLUENTS

One of the main drivers of economic expansion in Asian nations such as Bangladesh, Vietnam, Pakistan, Indonesia, China, and India, is the textile sector. Textile wastewater is thought to contain around 10,000 different dyes and chemicals, including polyester, acetic acid, caustic soda, organic glue, formic acid, and polyethylene emulsion. As Figure 2 illustrates, the aforementioned compounds have a detrimental effect on human health and disturb aqua life, growth of plants/crops etc. The complex mixture of chemicals and colours found in textile effluent, including dispersed dyes, has a significant potential for

mutagenicity, carcinogenicity, and teratogenicity. With an annual release of approximately 50,000 tonnes of dyes into the environment, textile wastewater discharge accounts for 20% of water pollution and has a significant negative impact on the ecosystem [5]. An average of 200 litres of water are needed to make 1 kilogramme of textiles. The wastewater produced in the textile production process frequently has very high loads of chemical and biological oxygen demand and is alkaline or basic [2]. The toxicity of the effluent is increased by the frequent use of heavy metals like copper and chromium as mordants in dye fixation [10].

Moreover, the chemicals found in dyeing effluents have the potential to upset aquatic microorganisms' delicate equilibrium, which could have an impact on the whole food chain. These contaminants can affect agricultural production, taint sources of drinking water, and endanger human health when they seep into soil and groundwater. Moreover, the discharge of wastewater from textile dyeing processes leads to the reduction of oxygen in water bodies, creating dead zones that are uninhabitable by aquatic life. Strict laws, effective wastewater treatment systems, and the promotion of sustainable dyeing techniques are necessary to reduce these negative impacts of textile dyeing operations [8,11].

Numerous studies have demonstrated that textile wastewater can cause dermatitis, illness, stress, haemorrhage, and skin ulcers. The highly carcinogenic dyes reduce photosynthetic activity and light penetration, which results in an oxygen shortage and restricts downstream beneficial uses including irrigation, drinking water, and recreation. Azo dyes are harmful, particularly in that they can cause cancer and mutations. They are ingested by the body; thereafter intestinal microbes metabolise them and destroy DNA. The textile industries are currently dealing with a serious problem of environmental pollution as a result of such a massive amount of wastewater that is dyed [2,11,12].

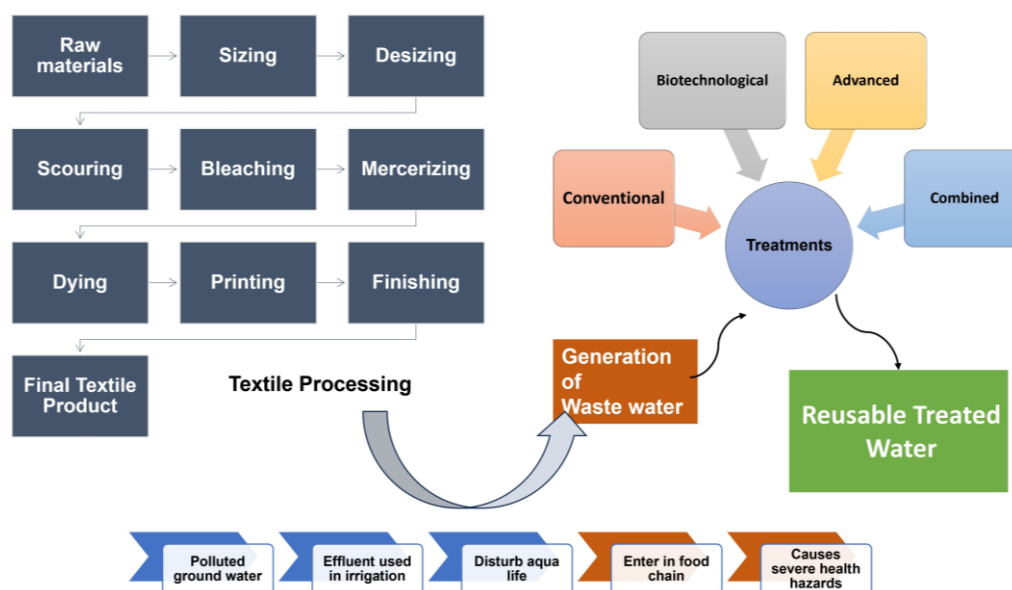


Figure 2. Textile processing, its negative impact and different treatment methods

ISSUES RELATED TO CONVENTIONAL METHODS OF TREATMENT

Textile dye effluents are typically treated primarily by industries through physical or chemical processes. Screening, filtration, ion exchange, adsorption etc. are the common techniques when considering physical methods of treatment [11]. Alum or ferrous sulphate chemical precipitation is a conventional technique for treating textile effluent. However, this process is expensive and produces a large amount of sludge, which harms the environment. As a result, many techniques, including adsorption, ozonation, filtration, biological treatment, and electrochemical treatment, have been developed for treating textile effluent [13]. According to Singh and Arora (2011), wastewater cannot be treated using the current conventional technologies in a way that satisfies discharge requirements [3]. The following reasons indicate the major drawbacks of the conventional techniques of treatments.

Complexity of Textile Effluents: A wide range of contaminants, including dyes, heavy metals, solvents, and other compounds, can be found in textile effluents. It may be difficult for physical and chemical methods to eliminate or break down each of these various pollutants at the same time [14].

Dye Stability: Under typical physical or chemical treatment procedures, a large number of textile dyes stay chemically stable and do not readily deteriorate. The advanced and specialised approach needed to efficiently break down these stable colour molecules [11]

Volume and Scale: Because textile industry effluents are frequently produced in enormous quantities, implementing physical and chemical treatment technologies on this scale is difficult and expensive. These systems may not be able to handle the amount of effluent due to its sheer volume [15].

Secondary Pollutants: Some chemical processes may result in secondary pollutants, which may be just as dangerous as the primary toxins or even more so. It can be difficult to manage these byproducts and may be necessary to take additional treatment measures [11,16].

Selective Removal: Some pollutants may be removed only by physical or chemical means, leaving other pollutants untreated. Combining many methods is frequently necessary to remove all pollutants completely [16].

Environmental Impact: Reagents and chemicals used in chemical treatment procedures may harm the environment if improperly handled. The movement of contaminants from one phase to another, such as from water to sludge, can present problems for disposal and the environment [11,14,15].

Owing to these difficulties, the treatment of textile wastewater often takes a holistic approach combining physical, chemical, and biological treatment techniques by dissolving complex organic molecules and increasing treatment efficiency overall. Furthermore, current research is concentrated on creating cutting-edge treatment technologies, like electrocoagulation, membrane processes, and nanotechnology-based strategies, to enhance the efficiency of treating textile effluent and overcome the drawbacks of traditional physical and chemical techniques [15].

DEGRADATION OF DYES BY BIOTECHNOLOGICAL APPROACHES

An essential field of study in environmental microbiology and biotechnology is biodegradation of dyes. Since many synthetic dyes have complicated chemical structures and are resistant to standard treatment techniques, it can be difficult to remove them from wastewater in a variety of industries, including the textile. A viable solution to this issue is provided by biodegradation, a natural process that is carried out by microorganisms. One of the earliest patents for a biological remediation agent was in 1974 and concerned a *Pseudomonas putida* strain that could break down petroleum [17].

Potential Bio-Based Remediation in Textile Effluent Treatment

To solve the environmental issues related to textile wastewater, bioremediation of textile effluents employing bacteria, fungi, and algae has attracted a lot of attention as a sustainable and environmentally friendly solution. Because they have special enzymatic systems, bacteria, fungi, and algae may degrade complex organic molecules and absorb different types of contaminants found in textile effluents. As they produce enzymes like oxidases and dehydrogenases, which can catalyse the breakdown of dyes and other organic pollutants, bacteria are essential to the process of biodegradation. By using microorganisms to immobilise textile dyes' chemical structures, bioremediation can cause degradation, mineralization, or transformation. Biological methods achieve complete dye mineralization and are economically viable, and suitable for usage even in underdeveloped nations. To treat textile dye effluent and transform dye molecules into non-toxic chemicals, feasible biological candidates include bacteria, algae, yeast, fungi, and enzyme-based systems (either individually or in consortia, under aerobic or anaerobic conditions).

After immobilising on sorghum, *Trametes versicolor* was used to investigate the removal of humic acid from both artificial and actual industrial effluent. It was observed by scholars that 80% of colour removal was accomplished for both simulated and actual wastewater [18]. A group of scientists conducted a study to test 11 types of bacterial strains for their capabilities in the degradation of orange II dye and concluded that to bioremediate textile effluents containing hazardous azo dyes like orange II, *B. subtilis* is a viable strain to utilise [19]. Another study was to assess eleven bacterial strains' capacity to degrade the azo dye methyl red. Based on preliminary screening data, *P. aeruginosa* was determined to be the most effective strain, with 81.49% degrading activity. *P. aeruginosa* is a useful strain for the detoxification and remediation of industrial effluent containing methyl red and other azo dyes, according to the findings of multiple experiments [20]. Hossen and coworkers claimed based on their studies that at least one of the eight reactive dyes used in the textile industries can be decoloured (showing decolourization of roughly 90%) by *Alcaligenes faecalis*, *Bacillus cereus*, and *Bacillus* sp. [21]. Pure strains of bacteria *Aeruginosa*, *Pseudomonas* and *Pantotropha Thiosphaera*

proved to be able to decolourize the dye even after adding the dye repeatedly [22]. Bacterial species, including *Cellulosimicrobium cellulans*, *Bacillus coagulans*, and *Microbacterium testaceum*, isolated from low-level liquid radioactive wastes, demonstrated substantial loading capacities for cerium and cobalt metal ions. *Microbacterium testaceum* exhibited particularly high capacities, reaching 68.1 mg g⁻¹ for Ce(III) and 49.6 mg g⁻¹ for Co(II), highlighting their potential as effective scavengers for these metals in liquid waste effluents [23].

The *Tetraselmis* sp. algae were modified using the surfactant cetyltrimethylammonium bromide (CTAB) to create the Tetra-Alg-CTAB adsorbent, utilized for adsorbing methyl orange and methylene blue solutions. Tetra-Alg-CTAB demonstrated efficient adsorption of both the dye, especially at pH 10, with pseudo-second-order kinetics and Freundlich adsorption isotherms. The modified adsorbent displayed robust performance, particularly in the repeated adsorption of anionic dye methylene blue, with over 70% efficiency even after 4 cycles [24].

The ability of fungi, especially white-rot fungus, to break down a variety of resistant substances, including artificial colours, is attributed to their ligninolytic enzymes, such as laccase and lignin peroxidase. Two fungi with filaments to remediate actual effluent from the textile sector, *Aspergillus carbonarius* and *Penicillium glabrum* were immobilised in macroporous polymeric support. The outcomes demonstrated that batch trials produced 98.2% decolourization and 69.8% COD removal efficiency. However, an up-flow packed bed bioreactor produced 78.8% decolourization and 67.7% COD removal efficiency. After operating the up-flow packed bed reactor repeatedly for three cycles, the colour and COD removal efficiencies were measured at 78.8%, 72.1%, 70.2% and 67.7%, 62.5%, and 60.0%, respectively [25]. *Pichia occidentalis*, a salt-tolerant yeast with the ability to decolourize a variety of azo dyes was tested. In ideal circumstances, over 98% of 50 mg per litre of Acid Red B can be decoloured in less than 16 hours [26].

Bellucci and colleagues observed seven wastewater samples produced by the textile digital printing sector were assessed for treatability using nitrogen removal techniques based on anammox, *Chlorella vulgaris* microalgae for biomass generation and nutrient uptake, white-rot fungi (*Phanerochaete chrysosporium* and *Pleurotus ostreatus*) for laccase activity and decolourization. Through statistical analysis, the biodegradative potential of each type of organism was ascertained in batch experiments and connected with the primary attributes of the textile wastewaters. All bacteria showed a significant deal of promise for treating and valorising textile wastewater after customised adaption phases, according to the findings [27]. To remediate actual effluent from the textile industry, the filamentous fungus *Aspergillus carbonarius* was used by Isik and associates to create a fungal bioactive ultrafiltration membrane. *Aspergillus carbonarius*, a filamentous fungus, has been seen to possess an open fibre at one end, which exhibits characteristics of a hollow fibre membrane with an outside radius

of less than 10 μm . The findings demonstrated that fungal bioactive ultrafiltration membranes produced 73.2% COD reduction and 91% wastewater decolourization [28].

Phytoremediation is becoming a more effective and environmentally acceptable method of cleaning up contaminated aquatic habitats as a result of ongoing studies in plant physiology and genetic engineering. Certain plant species can absorb and concentrate pollutants from the water into their tissues when living in watery habitats [29]. Water hyacinth (*Eichhornia crassipes*) and duckweed (*Lemna minor*), two aquatic plants used in phytoremediation, have broad root systems that offer a lot of surface area for absorbing pollutants from contaminated water bodies [30]. Through metabolic processes within the plants, the contaminants are either converted into less hazardous forms or sequestered in the biomass of the plants. However, careful selection of suitable plant species is necessary for efficient phytoremediation, taking into account variables like environmental circumstances and contaminant sensitivity.

Genetically Modified Microorganisms for increasing treatment efficiency

In the current situation, to deal with the complexity of the existing treatment techniques researchers around the world are focusing on the development of genetically modified microorganisms to make bioremediation more efficient (figure 3). Engineered microbial strains are produced by genetically modifying them to produce a stronger protein that enhances a desired feature. Using such bacteria, fungi, and algae, biodegradation of oil spills, halobenzoates, naphthalenes, toluenes, trichloroethylene, octanes, xylenes, etc., has been achieved [31]. The possibility of using genetically modified organisms and microbial consortia to increase the biodegradation efficiency of different dyes has been investigated by researchers. Furthermore, microbial cells and immobilised enzymes have been used to develop effective and reusable biodegradation systems. According to the results, immobilised mixed consortium cells (bacterium, *Brevibacillus latero sporus*, and yeast, *Galactomyces geotrichum*) on calcium alginate, polyvinyl alcohol, stainless steel sponge, and polyurethane foam can be regarded as an efficient tool for its potential application in the removal of xenobiotic textile dyes from the wastewater of the textile industry with >90% decolourization efficiency [6].

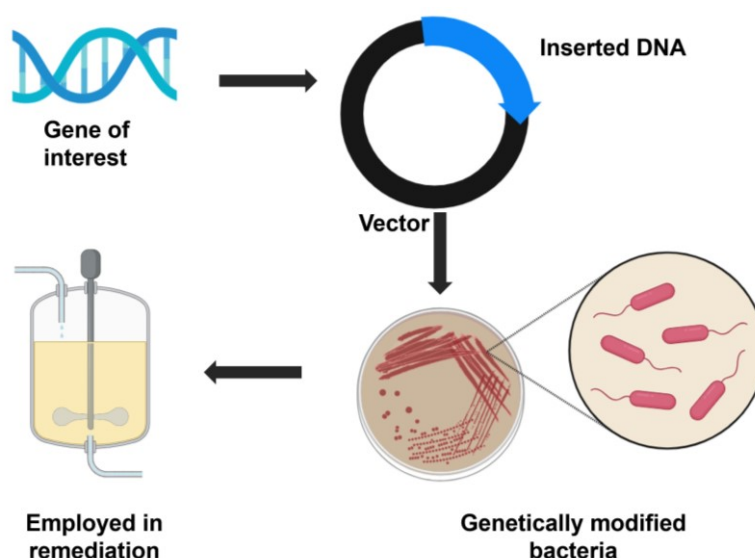


Figure 3. Genetically modified microorganisms in effluent remediation

One of the most important first steps towards creating sustainable and environmentally friendly techniques for treating wastewater containing dyes is understanding the mechanisms of dye biodegradation and optimising the conditions for microbial activity. This will ultimately lessen the environmental impact of the textile and other dye-dependent industries. While conventional treatments have not been successful in eliminating dangerous substances from the environment, advances in more recent remediation techniques may contribute to improving the quality of bioremediation.

Enzymatic degradation of dyes

Wastewater treatment using enzymatic degradation of textile effluents has shown promise and is ecologically benign. Textile effluents, which contain synthetic dyes and chemicals, can be largely degraded by a variety of enzymes (according to requirements). These enzymes catalyse the oxidation, reduction, and hydrolysis of dye molecules to produce simpler, less hazardous compounds. Numerous benefits come with enzymatic degradation, such as high efficiency, selectivity, and specificity for the contaminants being broken down. Enzymes may function in mild pH and temperature environments, which lowers the energy needed for treatment procedures. Furthermore, enzymatic treatment options are environmentally sustainable since they generate little or no toxic byproducts. For example, enzyme oxidoreductases such as laccases [32], azoreductases [33], and peroxidases [34] are the popular ones to oxidise dyes, both phenolic and non-phenolic, specialize in breaking down azo bonds inherent in azo dyes, and functions by catalysing the oxidation of dyes through the utilization of hydrogen peroxide, respectively.

One of the more promising newly established methods for removing the aforementioned chemicals is the utilization of immobilized enzymes. Enzyme stability and reusability are increased by immobilisation strategies, such as immobilising enzymes on different supports, which raises the effectiveness of enzymatic degradation processes even further. The development of novel enzymatic treatments that are both effective and financially feasible for large-scale textile effluent remediation could result from ongoing research in enzyme technology, which would examine enzyme engineering and optimisation. This would greatly contribute to the sustainable management of industrial wastewater [35]. The application of immobilised oxidoreductases, primarily laccases, tyrosinases, and peroxidases, in enzymatic procedures presents many benefits, such as low cost, sustainability, and/or gentle process conditions. Owing to their very poor substrate selectivity, immobilised oxidoreductases may efficiently convert a wide range of phenol and phenolic derivatives, such as drugs, oestrogens, bisphenols, and dyes, with clearance rates typically surpassing 90%. Additionally, immobilised enzymes show a high potential for recycling, enabling their repurposing in many catalytic cycles [36]. Table 1 below shows some of the potential applications of immobilized enzymes in the remediation of textile effluents in terms of dye degradation.

Table 1. Immobilized enzyme in the treatment of textile effluents

S. No.	Enzyme	Support (Immobilized on)	Property Enhancement	Reference
1.	Laccase	Polyacrylamide-alginate	It was observed that 55.6% of the dyes in textile effluent were removed and that 93.3-99.1% of the dyes in solution decoloured.	[37]
2.	Manganese peroxidase	MnP-Fe ₃ O ₄ -chitosan	Increased capacity to decolorize Methylene blue and reactive orange 16, with removal of 96% ± 2% and 98% ± 2%, respectively. The reusability of the synthesized nanocomposite was studied for five successive cycles showing the ability to retain its efficiency even after five cycles	[38]
3.	Peroxidase	Magnetic nanoparticles	A notable degree of stability against changes in pH and temperature. Furthermore, the immobilised peroxidase remained fully active after 90 days of storage at 4 and 25 °C and after recycling for up to 100 cycles	[34]
4.	Laccase	Fe ₃ O ₄ @SiO ₂	Demonstrated exceptional resistance to organic chemicals, inhibitors, and metal ions, along with enhanced thermal and pH stabilities and high reusability	[39]

The unique requirements of the effluent treatment, taking into account variables like the kind of contaminants, treatment goals, financial limits, and environmental circumstances, will determine

whether to use free enzymes or microorganisms. To fully utilise each strategy's benefits, a mix of the two may be employed in certain circumstances.

Employment of Microbial Consortia and Synergistic Approaches

In textile effluent remediation, synergistic approaches entail the integration of several treatment modalities, such as the combination of physical and chemical processes with microbial consortia. Wastewater treatment systems may operate better overall as a result of this integration [16]. For example, the physical pretreatment of effluents through coagulation or adsorption can remove big particles and increase the wastewater's biodegradability, which increases the waste water's susceptibility to microbial breakdown. Microbial consortia then have the ability to effectively target the leftover dissolved pollutants. In the biodegradation of textile effluent-containing dyes, bacteria have shown up to 100% efficiency. In numerous instances, bacterial consortia are more effective at removing dyes than a single strain [11]. Different species of microorganisms collaborate in microbial consortia to break down different types of contaminants. These consortia can target a wide range of pollutants in textile effluents because of their complementing metabolic capacities. For instance, certain microbes might be particularly good at degrading organic dyes, while others might be particularly good at removing stubborn substances or lowering heavy metal levels. In textile effluent remediation, the application of microbial consortia and synergistic techniques yields multiple advantages, such as increased treatment efficiency, shortened treatment times, and decreased energy and chemical consumption. In addition, it reduces the generation of hazardous byproducts and offers a more environmentally friendly way to address the problems brought on by textile wastewater. To further improve the remediation of textile effluents, research keeps concentrating on maximising the composition of microbial consortia, comprehending their interactions, and honing synergistic treatment procedures. It also keeps tackling emerging pollutants and enhancing cost-effectiveness [40].

Bioreactor Systems as Green Infrastructure

Bioreactor systems, which provide a regulated and ideal environment for the development and activity of microorganisms or enzymes engaged in biodegradation processes, have shown extraordinary efficacy in the remediation of textile effluents. These specially designed systems offer a regulated environment that guarantees ideal parameters for their activity. In a continuous reactor, like packed bed reactors, immobilised microbial cells and/or enzymes can be easily employed, opening the door to large-scale wastewater treatment, process automation, scalability, and high performance [41]. Numerous closed bioreactor system designs have already been put out to improve growth and regulate operational parameters.

Table 2. Treatment method comparative analysis

	Treatment Systems	Advantages	Disadvantages	Industrial Application	References
Conventional methods	Physical (adsorption/filtration)	Effectively remove large particles and colourants - simple operation and low energy requirements	Ineffective for dyes with low molecular weight	Used only to separate large particles	[42]
	Chemical (coagulation/flocculation /precipitation/oxidation/reduction)	Effective for a wide range of dyes and contaminants	Chemical costs can be high, toxic byproduct generation	Extensively used for its versatility in treating various types of dyes	[43]
	Biological treatment (activated sludge process / biological aerated filters)	Natural degradation of dyes	Long start-up time - vulnerability to shock loads	Widely used due to its cost-effectiveness and sustainable nature	[44]
Biotechnological methods	Microbial bioremediation	Environmentally friendly approach	Limited effectiveness for certain complex dye structures	Being explored	[45]
	Enzymatic bioremediation	Highly specific enzymatic action for targeted dye degradation	Costly production and application of enzymes	Being explored	[46]
	Phytoremediation	Utilizes plants to uptake and degrade contaminants	Time-consuming, and limited to certain types of dye.	Being explored	[47]
	Biosorption	Utilizes biomaterials for dye adsorption	Limited capacity and efficiency, longer time requirements, low stability/durability	Used as a secondary treatment or as part of a multistep treatment process	[48]

Nanotechnology Associated Treatment

Nanoparticle-mediated textile effluent degradation has drawn interest as a cutting-edge method in wastewater treatment research. Owing to their large surface area to volume ratio and distinct reactivity, nanoparticles have a remarkable ability to absorb and/or break down complex organic contaminants, such as chemicals and pigments found in textile effluents boosting the photocatalysis process efficiency [49]. When stimulated by light or other external stimuli, a variety of nanoparticles forms, including copper nanoparticles (Cu) [50], titanium dioxide (TiO₂) [51], silver nanoparticles (Ag)

[52], and iron-based nanoparticles [53], magnesium oxide (MgO) [54] have shown catalytic and photocatalytic capabilities that enable them to degrade organic molecules. These nanoparticles can either adsorb or catalyse the breakdown of dyes in textile effluents through processes such as photocatalysis, which produces reactive oxygen species when exposed to light. The dye molecules are then oxidised and broken down by the reactive oxygen species into less toxic and simpler substances. Treatments based on nanoparticles have demonstrated excellent efficacy, quick rates of degradation, and versatility in addressing many types of contaminants. Excellent adsorption qualities of nanomaterials can lessen the demand for conventional chemical flocculants and coagulants. Saving money on the procurement and management of these chemicals results from this [55].

To clean up textile effluent, alum and ferromagnetic nanoparticles were combined by a group of researchers to create a composite magnetic coagulant. The coagulation performance for the removal of colour, turbidity, and certain heavy metals (Al, Cu, Fe, Zn, and Mg) was assessed. The result indicated 85% and 82% elimination of colour and turbidity, respectively. It also projected 85% desirability. This system outperformed alum (40–75%) in the removal of both organics and heavy metals, exhibiting an 80–95% improvement in efficacy. Consequently, authors claimed the use of superparamagnetic nanocomposite as an environmentally benign and efficient coagulant for the removal of heavy metals and their byproduct pollutants is anticipated in the context of water and wastewater systems [56]. In another case, the wastewater from the textile sector was treated using surface-modified nanoparticles (particle size smaller than 335 nm). Using different combinations of the pH of the effluent solution, contact time, dosage of nanoparticles, and stirring speed, many batch experimental studies were carried out by scientists to treat the wastewater from the textile sector. The outcome of the experiment shows that the contaminants in the textile industry wastewater may be effectively reduced by the surface-modified particles in terms of Chemical Oxygen Demand, Total Dissolved Solids, Total Suspended Solids, Dissolved Oxygen, Turbidity, and Conductivity [57]. Fouda and coworkers reported the reduction of total suspended solids (TSS), total dissolved solids (TDS), and chemical oxygen demand (COD) levels at percentages of 86.9%, 77.0% and 89.3%, respectively, for textile effluent used to monitor the quality of treated effluents under ideal experimental conditions and in solar radiation. MgO nanoparticles demonstrated their efficacy in treating textile effluents for four cycles based on their reusability [54]. Some of the potential application of nanoparticle-based remediation is summarized in Table 3.

Chemically produced nanoparticles typically have a strong propensity to aggregate, which can drastically lower their efficiency and make them unstable. The toxic chemicals utilised in the production and stabilisation of nanoparticles produce hazardous byproducts. These shortcomings motivate scientists to discover a different process for the stable and non-toxic manufacturing of green

nanoparticles. Because the synthesis of nanoparticles in plant extracts is a safe and environmentally acceptable approach, there has been a lot of interest in creating a new pathway for researchers to identify the compounds. Due to their safety, sustainable methods, lack of hazardous byproducts, and ability to clean dye-contaminated water, green nanoparticles are among the most effective and cutting-edge options available [5].

Biosorption is also considered a form of bioremediation technique that refers to the passive uptake or binding of pollutants, such as heavy metals or organic contaminants, by biological materials like bacteria, fungi, algae, or other biomaterials and/or their derivatives. A novel magnetic adsorbent was derived from activated carbon obtained from rubber fruit shells by a group of researchers. The material, modified with magnetite particle coating and silanization, demonstrates structural success as confirmed by IR spectroscopy and EDX diffractogram. It exhibited efficient adsorption of methylene blue and crystal violet dyes in both mono-component and bi-component solutions. Optimal conditions were observed at pH 8 with a 60-minute interaction time. The material's adsorption kinetics align with the pseudo-second-order model, and the Langmuir isotherm model describes bi-component adsorption. This innovation displayed reusable adsorption capability exceeding 80%, making it an effective and sustainable solution for dye removal [58]. According to scholars in this area like Mashabi and colleagues, the most promising sorbents for wastewater treatment emerge from chitosan and glycidyl methacrylate, owing to their diverse attributes such as availability, stability, high sorption capacity, and durability. Their derivatives exhibited excellent water-purification properties, proving effectiveness in cleaning wastewater. Noteworthy instances include a carboxymethylated chitosan-conjugated magnetic nano-adsorbent displaying a remarkable adsorption capacity for Acid Orange 12 dye, and GMA-substituted dextran with acrylic acid exhibiting significant efficacy against methylene blue. Scholars recommended further exploration of the chitosan and glycidyl methacrylate hybrid material for its potential to develop more efficient contaminant-removal methods. This suggestion aims to bridge the existing gap between laboratory findings and practical industrial applications [59]. A cost-effective method was developed to modify chitosan using a non-catalytic direct condensation reaction with gallic and caffeic acids, producing condensation adduct resins RI and RII. These resins exhibited enhanced silver ion adsorption compared to pure chitosan, with maximum capacities of 300 and 278 mg/g, and high reusability using a 0.01 M nitric acid solution. The process demonstrated efficient removal of toxic silver ions from aqueous solutions [60].

The biological approach, while inherently sustainable, is notably time-consuming. In contrast, the utilization of nanoparticles for mediating remediation in dye degradation presents a comparatively expeditious methodology that effectively eliminates heavy metals and degrades dyes without generating toxic byproducts, a departure from conventional techniques. These nanoparticles also

exhibit the capacity to facilitate enzyme-based remediation processes by enhancing enzyme stability and promoting reusability, thereby contributing to cost reduction. Furthermore, the emergence of environmentally conscious methods for fabricating these nanoparticles underscores a promising shift towards sustainable alternatives in remediation strategies [34]. Although there is a lot of potential in this technique, further research is needed to fully understand the long-term consequences of nanoparticles, optimise their properties, and create scalable and affordable systems for degrading textile effluents with nanoparticles.

Table 3. Textile effluent remediation by nanoparticles

S. No.	Nano particles	Remediation	References
1.	Cu nanoparticles	As per the Azo dye degradation experiments, after 5 hours of exposure to sunshine, able to decolour congo red (97.07%), malachite green (90.55%), direct blue 1 (88.42%), and reactive black 5 (83.61%). When compared to the untreated samples, the treatment of textile effluents with nanoparticles significantly reduced the following: pH, electrical conductivity, turbidity, total suspended particles, total dissolved solids, hardness, chlorides, and sulphates.	[50]
2.	ZnO nanoparticles	Many dyes, including reactive black 5 and methanol blue, were completely (>90%) decoloured as a result of the catalytic nanoparticles. The COD, TDS, EC, pH, and colour of two types of actual wastewaters that had been injected with reactive black 5 and reactive red 120 were likewise significantly reduced.	[61]
3.	MgO nanoparticles	Analysis showed that treatment in the presence of sunshine achieved the maximum decolourization of genuine textile effluents (92.8%) after 180 minutes. MgO-nanoparticles proved to be reusable over a four-cycle period. Significant adsorption capacity for common tannery heavy metals, such as Cr, Co, Pb, Cd, and Ni, was also demonstrated.	[54]
4.	Fe ₃ O ₄ Nanoparticles Coated with EDTA and Ag nanoparticles	The results of the analyses indicated that after 180 minutes, the highest decolourization of real textile effluents (92.8%) was accomplished in the presence of sunshine. The efficiency maintained over a four-cycle period was proved by their reusable nature. Biosynthesized MgO-NPs showed a significant adsorption capability including Cr, Co, Pb, Cd, and Ni. Testing for recycling revealed that Fe ₃ O ₄ @EDTA-Ag has good stability; after ten recycling cycles, the catalyst's reduction rate decreased by only about 4.5%.	[53]
5.	Ag nanoparticles on AgTi ₂ (PO ₄) ₃	Good catalytic activity, with an efficiency and reaction time of around 96.30% and 320 seconds for the methylene blue reduction and approximately 94.60% and 270 s for the methyl orange reduction, respectively.	[62]

S. No.	Nano particles	Remediation	References
6.	Au nanoparticles	Demonstrated catalytic activity with a higher than 99% rate of degradation in 10–30 minutes for the azo-dye reduction.	[63]
7.	Fe-based nanoparticles	Strong adsorption capacity and stability in suspension media have made them useful for treating dyes (e.g., Methyl orange and methylene blue) in wastewater from the textile industry.	[64]
8.	Magnetic iron oxide combined with carbon nanoparticles	Examining the effectiveness of removing methyl orange and phenol, it was found that the nanocomposites exhibited greater interactions with the dye, with the carbon concentration being a key factor in the adsorbent behaviour of the nanoparticles.	[65]
9.	Magnetized nanoparticle	Eliminated colour (85%) and turbidity (82%). Outperformed alum (40–75%) in the removal of both organic pollutants and heavy metals, exhibiting an 80–95% improvement in efficacy.	[56]
10.	Silica nanoparticle	Able to reduce pollutants in terms of COD, TDS, TSS, DO, turbidity and conductivity.	[66]

ENVIRONMENTAL AND ECONOMIC BENEFITS OF BIOTECHNOLOGICAL TREATMENT METHODS

Researchers across diverse fields are collaboratively exploring innovative strategies that are diligently focused on mitigating environmental challenges through the reduction and reuse of waste, thereby fostering sustainability, circular economy principles, and industrial symbiosis [67,68]. For the treatment of textile effluents, biotechnological treatment techniques provide considerable economic and environmental advantages. These techniques offer a sustainable means of managing the various contaminants present in wastewater from textile industries. When used in biotechnological treatments, microorganisms and enzymes effectively break down a broad variety of chemicals and dye chemicals into less toxic forms. Biotechnological processes, as opposed to conventional approaches, frequently produce fewer secondary pollutants and reduce the total environmental impact, protecting human health and aquatic ecosystems in the process. Additionally, by more effectively utilising water resources, the biodegradation of textile effluents lessens the burden on natural resources. Additionally, biodegradation procedures produce less sludge, which reduces disposal expenses. Moreover, the application of biotechnological techniques advances the notion of the circular economy, which minimises the requirement for freshwater intake and wastewater outflow by allowing treated water to be recycled inside the business.

According to researchers like Adane and Adugna, applying dye removal is limited by the influence membrane filtration method's cost and blockage. The complete mineralization of dyes, low working expenses, and minimal by-product creation such as solid wastes make the biological treatment approach superior to the chemical treatment process. Before introducing the wastewater to the

microbial treatment process, chemical technique pretreatment was crucial to reducing the load on the microorganisms and obtaining high-quality output. Compared to physical and chemical methods, the biodegradation process has the following advantages such as being eco-friendly, low-cost, low infrastructure, and operating costs, low solid wastes, complete mineralization into nontoxic end products, etc. [15].

Bioremediation is an on-site technique that poses no risk and is both economical and ecologically benign [69]. Another group of researchers also claims that because bioremediation uses less energy than landfilling and incineration of wastewater solids, it is a more cost-effective and eco-friendly option for treating textile wastewater [1]. According to another scholar, it has been discovered that biological treatment systems are more cost-effective and efficient than conventional wastewater treatment techniques. Since microbial decolourization doesn't create any intermediate byproducts, it is more cost-effective and environmentally friendly. It can also effectively mineralize the dyes. When it comes to implementation costs, bioremediation is typically more economical. In comparison to other traditional approaches, it frequently entails fewer capital expenditures and requires less infrastructure. Compared to traditional methods, bioremediation frequently has cheaper operating and maintenance expenses. The biological system can frequently function with little assistance once it is formed. Because bioremediation relies on natural biological processes, its energy requirements are typically lower. Even though bioremediation is frequently a slower process, in the long run, it may be more sustainable. Contaminants naturally break down over time thanks to microorganisms. Because it depends on natural processes, it can be effective for a long time, especially for persistent toxins. It should be considered, nevertheless, that site-specific factors, such as temperature, pH, and the presence of specific toxins, might affect how efficient bioremediation is. Its widespread perception as environmentally friendly could help it gain public acceptability.

Some of the recently published articles mentioning recommended approaches to enhance bioremediation as well as the overall treatment process are summarized in Table 4.

Table 4. Recommended Integrated Remediation Approach

S. No.	Recommended Remediation	Additional Approach Recommended	Future Potential	Reference
1.	Bioremediation	Hybridize bioremediation with nanofiltration	Can effectively reduce chemical oxygen demand (COD). It can eliminate over 90% of the colour including denim washing wastewater contaminated with indigo dye.	[70]
2.	Bioremediation	Combining bioremediation with nanofiltration	With a mean unit cost of 0.97 USD/m3, promising and cost-effective alternative to existing commercial purification processes	[70]

S. No.	Recommended Remediation	Additional Approach Recommended	Future Potential	Reference
3.	Bioremediation	Collaboration of bioremediation and coagulation & flocculation	Can achieve better yields	[71]
4.	Bioremediation	Should be blended with other interdisciplinary approaches	It holds promise for addressing the degradation of non-biodegradable dyes and the treatment of complex pollutants. However, advancing technology is essential to overcome the time-consuming nature of the current approach.	[1]
5.	Bioremediation	Combined methods (physical, chemical and biological) and constructed wetlands processes	Exceptionally efficient in breaking down and purifying wastewater from textile processes, demonstrating a high level of effectiveness in the degradation and detoxification of such industrial effluents	[72]
6.	Bioremediation	Additional Omics approach	Promising tools for a comprehensive understanding of microbial-mediated bioremediation. Hold immense potential in predicting organism metabolism in polluted environments and facilitating efficient bioremediation strategies	[73]
7.	Bioremediation	Integrating biological processes, minimizing chemical coagulant usage	The Effluent Treatment Plant (ETP) system should exclusively handle dye effluents without mixing them with household sewage	[74]

CONCLUSION AND FUTURE RECOMMENDATION

The global textile market is predicted to grow increasingly, which would coincide with an increase in water pollution caused by large volumes of textile dye-rich effluents. 20% of the world's industrial water pollution is attributed to the textile industry, which poses significant environmental problems. These effluents contain a complex mixture of chemicals, heavy metals, artificial colouring, and other contaminants, which can damage natural water bodies, jeopardise aquatic life, interfere in the food chain and eventually lead to long-term effects on health as well as the environment. Traditional techniques for treating textile effluents have drawbacks such as high setup costs and the generation of toxic by-products. This effluent doesn't turn into suitable water to use in agriculture, industries, or households even after this treatment. In response to these challenges, biotechnological approaches have been suggested as alternatives. However, it has been observed that relying solely on one of these methods is insufficient for establishing a truly sustainable approach to textile dye treatments. This review-based article outlines the most recent developments and knowledge regarding the remediation

process and then analyses it to determine the most viable course of action to address the aforementioned problems. The prospects for this field going forward were discussed. Our investigation diverges from the norm by critically examining biotechnological processes for textile dye effluent treatment. Going beyond mere criticism, our work not only evaluates but also champions a synergistic remediation approach. This innovative strategy seamlessly combines both conventional and non-conventional treatment processes, providing a holistic and comprehensive solution.

Observation from several researchers states that the integration of bioremediation using bacteria, fungi, algae, plants or enzymes with the traditional methods of treatment can be fruitful. The bio-based technique to remediate dye-containing wastewater is more widely accepted, ecologically benign, and economically viable. It was found that a synergistic approach is a great option while applying practically in industries, the integration of several treatment modalities, such as the combination of some remediation processes facilitates the efficiency. Specifically, when used in a bioreactor, in situ bioremediation makes it easier to reuse microorganisms and enzymes. By encouraging the frequent employment of enzymes and microorganisms, this strategy eventually promotes an economically feasible approach. Utilization of immobilized enzymes/microbes in reactors promotes reuse and eventually development of an economical approach. Reuse of the effluent water after treatment can accelerate good industrial ecology. Moreover, scientists around the world also propose modifying microorganisms genetically according to requirements can enhance the specificity to degrade dye and toxic pollutants in the wastewater. Furthermore, there is an emerging area of nanotechnology, that proposes the huge potential of nanoparticles in terms of their high absorbance capacity; can absorb and separate various substances including heavy metals from water. It is also notable that the utilization of nanoparticles to immobilize enzymes stabilizes the enzymes and facilitates reusability. Nano remediation holds future potential but is currently not in a state of application in a broader range/industrially. However, there is very limited data regarding the toxicity associated with the nanoparticles. Although there are challenges regarding the complexity of textile dye in effluents right now, there are multiple options available. Integration of the newer opportunities as discussed earlier in the paper, has great potential to solve the issue associated with dye-containing textile effluents. The treated water can be used by the same or different industries encouraging circular economy and industrial symbiosis, respectively.

Author Contributions

Conceptualization – Rahman M; methodology – Tabassum Z and Rahman M; formal analysis – Tabassum Z and Rahman M; investigation – Tabassum Z; resources – Rahman M; writing-original draft preparation – Tabassum Z; writing-review and editing – Tabassum Z and Rahman M; visualization – Rahman M. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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