

TEXTILE EFFLUENT TREATMENT METHODS AND LIMITATIONS: A SUSTAINABLE AND ECOLOGICAL ASPECT

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Abstract

Industrial wastewater causes water and soil pollution, leading to life-threatening issues. Wastewater comprises several dyes, detergents, phenols, chemical salts, and heavy metals which enhance temperature, pH, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) load, total suspended solids, Total Dissolved Solids (TDS), chlorides, sulfate, and nitrate of affected sites. Dye effluent is highly toxic and leads to mutagenic and carcinogenic outcomes on living beings. Environmental laws are being passed more frequently to control mostly azo-based dyes in the environment. The effluent must be treated before being discarded directly into the ecological ecosystem so that it can be reutilised and recycled for domestic purposes. In the present scenario, using a physicochemical-based approach is inefficient for eliminating contaminants as the process is expensive, and a secondary pollutant, sludge, is produced after the treatment. Being cheap and eco-friendly, the therapy of dye-laden water using microorganisms is a trend. The authors of the current review study have tried to bridge the gap in the bioremediation of dye wastewater. The review imparts an overview of the textile industry, the generation of wastewater by it, the environmental pollution caused, and its impact on the ecosystem. The discussion mainly focuses on the detailed analysis of the last few decades on the decolorisation efficiencies of numerous bioremediation techniques involved in treating textile dye effluent. Additionally, the authors have tried to include the most recent developments in this area. By using eco-friendly methods, this study will undoubtedly help dyestuff companies and researchers.

Keywords: Bioremediation; Environmental Pollution; Microbes; Textile Wastewater

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Introduction

The textile sector holds a significant position, is the second-largest employer after agriculture, and is an essential contributor to the Indian economy. Indian textile industry is helping to achieve a bio-economy objective of \$100 billion by 2025, along with a growth of 20% annually (Srivastava and Bandhu, 2022). There are around 3400 operating textile processing units in India, which contribute to the national GDP of about 4%, 27% of income in export, and in addition to around 14% of the Index of Industrial Production (IIP) (Kishor *et al.*, 2021). Handloom, handicraft, and small-scale sectors are three major traditional units in the textile industry that play a consequential part in the employment of the populations of semi-urban and urban areas. Also, these sectors have kept up India's old traditional prints and designs. Textile manufacturing industries utilize natural fibers, such as jute, cotton, wool, rayon, silk, linen, nylon, acrylic, polyester, etc., in synthetic fibers (Halim *et al.*, 2021). Cotton production in India is ranked first in the world, i.e., around 345 lakh bales (2016-2017), and second in cotton export (Kishor *et al.*, 2020). In the transition of the modern economy from a linear to a circular bio-based economy, sustainable development is a critical component. Exploration and implementation of current biotechnology advances for wastewater treatment constitute a sustainable environment and circular economy globally (Srivastava and Bandhu, 2022). Water consumption and generation of wastewater are completely dependent on the steps involved in the processing stages in textile industries (Ahmad *et al.*, 2022). During textile processing, several stages of wet operations include resizing and sizing, scouring, bleaching, mercerizing, dyeing/printing, and finishing, as shown in Figure 1. On that account, textile industry effluent is a global concern as the dyeing units consume humongous volumes of potable water, a battery of chemicals, and noxious dye molecules.

Textile effluent is one of the critical origins of environmental disruption due to the massive quantity of undesirable industrial wastewater released. It was also mentioned that for the 80,000 kg of fabric production, the textile industries consume a million liters of water (Moyo *et al.*, 2022; Sudarshan *et al.*, 2022). Among several processing stages, the dyeing and washing operations discharge 17-20 % of wastewater. Synthetic commercial dyes are applied in various industries, such as food, leather, paint paper printing, cosmetics, pigments, plastics, pharmaceutical industries, and the textile sector (Ahmad *et al.*, 2022). Dye-laden wastewater is distinguished as dark or bright-coloured, alkaline wastewater carrying higher measured temperature, Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Total Suspended Solids (TSS), Total Dissolved Solids (TDS), sulfates, nitrates, chloride, and phosphate. Textile wastewater carries a range of toxic inorganic and organic contaminants that are precarious to the ecosystem and public health (Kishor *et al.*, 2020; Saxena *et al.*, 2020). A variety of different chemicals, viz., detergents, acids, complex dyes, alkalis, salts, humectants, binders, dispersants, hydrogen peroxide, formaldehyde, surfactants, reducing agents, aromatic amines, and dioxin are dispensed in the textile effluent (Parmar and Shukla, 2018). Dyes such as Congo red, Methyl red, Coomassie brilliant blue, Methyl orange, orange, Methylene blue, Reactive blue, Remazol brilliant blue, and many more are found in the effluent along with other chemicals (Slama *et al.*, 2021). In 1856, the first synthetic, as well as organic dye, mauve, was formed by Perkin (Druding, 2021). After that, quite a variety of synthetic dyes have been appended to the ever-increasing record of dyes because of their durability, color fastness, and variety of shades over natural dyes. To a large extent, azo dyes are utilized in textile industries. Textile dyestuffs are

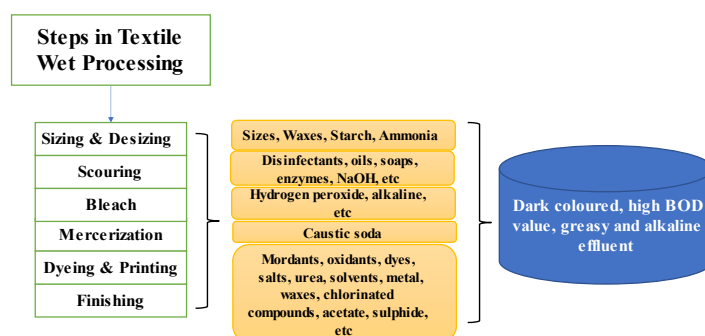


Figure 1. Steps in textile processing and wastewater generated

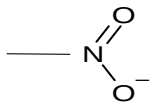
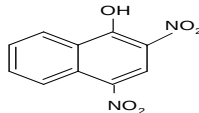
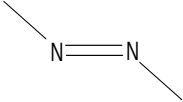
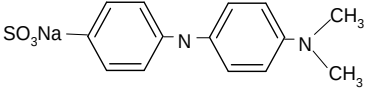
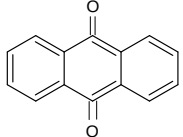
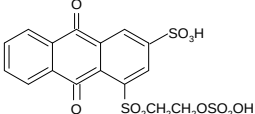
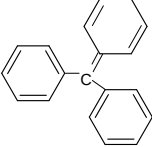
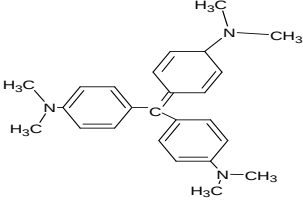
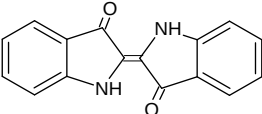
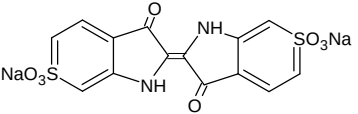
pigment-containing water-soluble chemical substances. It has been estimated that about 2-10% of the unused dye is directly lost into the aqueous wastewater during wet processing (Lellis *et al.*, 2019; Chaurasia and Kumar, 2022a). Table 1 gives the distinctive characteristics and constituents of the raw untreated effluent in India. Contaminated water can easily be remarked by the colour washed off into it, which indicates that the water body receiving it is critically depreciated. The textile pigments are

strong enough to be perceptible even at a low concentration, i.e., one ppm in water (Kishor *et al.*, 2021; Moyo *et al.*, 2022). Several types of artificial dyes are employed in the dyeing and printing sectors. These colorants are classified based on the presence of chromophore groups, such as azo dyes, anthraquinone dyes, disperse dyes, nitroso dyes, indigo dyes, and triphenylmethane dyes depicted in Table 2 (El-Harfi and El-Harfi, 2017). Dyes are further classified based on the reaction with textile

Table 1. Characteristics and constituents of textile industry raw effluent (Ramachandran *et al.*, 2013)

S. No.	Parameters	Textile Raw Effluent	S. No.	Parameters	Textile Raw Effluent
1	pH	10.5	13	Fluoride (mg/l)	0.64
2	Color (A 559)	1.202	14	Phosphate (mg/l)	345.3
3	Electrical Conductivity (mV)	109	15	Aluminum (mg/l)	<0.01
4	Chemical Oxygen Demand (mg/l)	1,512	16	Barium (mg/l)	<0.01
5	Biological Oxygen Demand (mg/l)	90.64	17	Total Iron (mg/l)	0.77
6	Total Hardness (mg/l)	86.5	18	Arsenic (mg/l)	<0.2
7	Surfactants (mg/l)	1.1	19	Chromium (mg/l)	<0.005
8	Cyanide (mg/l)	0.2	20	Cobalt (mg/l)	<0.007
9	Sodium (%)	70	21	Boron (mg/l)	<2.0
10	Phenolic Compounds (mg/l)	0.077	22	Copper (mg/l)	0.2
11	Nitrate (mg/l)	2	23	Lead (mg/l)	<0.02
12	Sulfate (mg/l)	345.3	24	Cadmium (mg/l)	<0.005

Table 2. List of textile dyes and their structure with examples

Class	Chromophore	Example
Nitro Dyes		 Acid Yellow 24
Azo Dyes		 Methyl Orange
Anthraquinone Dyes		 Reactive Blue 19
Trimethylmethane Dyes		 Methyl Orange
Indigoid Dyes		 Acid Blue 71

fibres and loss during the reaction indicated in Table 3. Dyes, when dissolved, hamper sunlight and decrease dissolved oxygen content in water, affecting the aquatic flora and fauna. It was also observed that heavy metals such as copper, arsenic, chromium, cadmium, nickel, lead, mercury, and zinc were present in textile wastewater (Kishor *et al.*, 2021). These heavy metals are non-corrodible and can be hoarded up in the living tissue via the food chain. Bioaccumulation can give rise to alarming health risks such as dermatitis, diarrhea, liver, central nervous system disorder, hemorrhage, neuromuscular disorder, kidney disorder, and failure (Khan and Malik, 2018). In plants, these metals also affect growth parameters such as retardation in seed germinating plantlets' growth and depletion in the soil microbial community by hampering their activity and growth (Chaurasia *et al.*, 2022b). Industrial effluents also disrupt the biogeochemical cycle by disturbing the soil niche and, therefore, giving rise to soil pollution. Azo dyes and subsequent metabolites have already been marked as carcinogens and mutagens. The detoxification and degradation of complex compounds are of utmost importance for the safe disposal of effluent into the ecosystem. Even the partially degraded azo dye compounds, aromatic amines, are secondary by-products and are toxic and mutagenic. It became evident that traditional methods cannot eliminate the color and xenobiotic compounds from the textile dye effluent because of the high stability and recalcitrant feature of the complex structure of dye molecules. The complex structure makes it nonbiodegradable, causing health hazards (Rathour *et al.*, 2019). If wastewater effluent is discharged without treatment into the aquatic ecosystems, dyes and other contaminants may enter the food web. It can lead to bioaccumulation and biomagnification. Textile wastewater also disrupts photosynthesis and can pose a mutagenic and carcinogenic impact on living organisms. Removal of these pollutants is essential but requires a set of complex procedures to remove contaminants from water. It has already been reported, and several methods have been proposed to remove or reduce anthropogenic contaminants from wastewater (Deng *et al.*, 2020). Physical,

chemical, and biotechnological methods have been acclimated to eliminate harmful pollutants with varying potency. Removal of the recalcitrant and xenobiotic compounds of the textile dye effluents constitutes a challenging task. Physiochemical treatment led to the formation of secondary pollution because of sludge. It is essential to develop environment-friendly techniques for purifying textile dye wastewater (Bhatia *et al.*, 2017). Earlier research has demonstrated the employment of biological approaches, such as the mineralization of textile colorants by utilizing cultures of bacteria, yeast, fungus, and algae, which are beneficial in the eco-friendly treatment of effluent. Enzymes secreted by bacteria, fungi, and algae, such as azo reductases, oxidoreductases, laccases, lignin peroxidases, etc., mediated the biodegradation of textile dyes in a feasible manner (Mishra and Maiti, 2019).

Although a multidisciplinary treatment approach is used, there is still a lack of strict regulation for zero discharge by Indian environmental policy. An environmental law of Zero liquid discharge (ZLD) from a textile industrial unit in India has been regulated by the National Green Tribunal to recycle, collect, and ensure zero wastewater discharge to the environment. ZLD system uses various modern wastewater treatment technologies. Achieving economies of scale in wastewater treatment becomes difficult in India due to the industry's extreme fragmentation (Brydges, 2021). The cluster of dyeing industries is widely dispersed; therefore, collecting and treating effluents becomes challenging. However, some technologies are now accessible, making ZLD systems economically viable and effective. The present review depicts the techniques for eliminating effluent pollutants using conventional and emerging biotechnological approaches. The significant research gap is dumping untreated wastewater into a nearby pond or river instead of the Common Effluent Treatment Plant (CETP). Our case study mainly focuses on the Sanganer region of Jaipur, Rajasthan, which has numerous dumping sites for untreated industrial wastewater, threatening the ecosystem. The colored water in Figure 2 was discharged from a small-scale textile unit, and the

Table 3. Degree of fixation of dyes to different fibres and loss to the effluent (Kadam *et al.*, 2022)

Dye Class	Fibre/ Substrate	Degree of Fixation	Loss in Effluent
Acid dyes (azo, anthraquinone, triphenylmethane)	Polyamide	89-95 %	5-20 %
Basic dyes (azo, anthraquinone, triarylmethane)	Acrylic	95-100 %	0-5 %
Disperse dyes (azo, nitro, anthraquinone)	Cellulose	70-95 %	5-30 %
Direct dyes (azo)	Polyester	90-100 %	0-10 %
Reactive dyes (azo, anthraquinone, basic)	Cellulose	50-90 %	10-50 %
Sulfur dyes (intermediate structures)	Cellulose	60-90 %	10-40 %
Vat dyes (anthraquinone, indigoids)	Cellulose	80-95 %	5-20 %
Metal-complex dye (azo, anthraquinone)	Wool	90-98 %	2-10 %

parameters of the water ecosystem were altered by the raw effluent in Table 1.

Treatment Approaches

Industrial wastewater is the foremost polluting constituent. Several treatment procedures are applicable for curing textile dye industrial wastewater and eliminating xenobiotic compounds. The conventional techniques acquired to alleviate the effluent are physical-chemical methods (conventional) and biological methods, Figure 3. The advantages and disadvantages of physiochemical methods have been depicted in Table 4.

Physical Methods

Screening and Sedimentation

At first, suspended solids, gritty materials, oil, and grease are removed. Coarse suspended materials like lint, fabric pieces, and yarn are screened through bar screens and fine screens and undergo settling to extract suspended particles (Chaurasia and Kumar, 2022a).

Coagulation and Flocculation

Strong coagulants thicken impurities, like ferric sulfate, ferric chloride, ferrous sulfate, lime, and alum. Studies have also reported the successful applications of other coagulants such as magnesium chloride, poly aluminum chloride, chitosan,

Table 4. Advantages and Disadvantages of Various Physiochemical Treatment Techniques

Physical and Chemical Treatment Methods	Process/Techniques	Advantages	Disadvantages
Coagulation-flocculation	Addition of coagulants	Simple and economically feasible	A large amount of sludge production. Handling and disposal issues, poor result with acid dyes
Membrane separation	Segregating particles by membrane	All chemical dyes decolourised	Expensive, incapable of large-scale treatment
Adsorption on activated carbon	Dye removal on a solid support	Easy, reusable, low cost, convenient, and no chemical is produced. Effectively remove dyes from effluent.	Inexpensive against disperse and vat dyes, requires long retention time.
Ion exchange	Ion- Exchange resin	Frequently used with no loss of absorbent	Not practical for disperse dyes, Regeneration is a possible Economic constraint.
Irradiation	Reacting with radiation dose and availability of oxygen	Effective for small-scale industry	A considerable amount of dissolved oxygen is needed, and expensive
Oxidation	Reacting with ozone gas	Efficient and rapid	High energy cost, Short shelf life
Fenton's reagent	Oxidation by Hydrogen peroxide - Fe	Efficiently remove colours of insoluble and soluble dyes	Expensive and solid waste production
Photochemical	Oxidation by Hydrogen peroxide - UV	- Removes dyes from textile wastewater - Removes industrial pollutants from textile wastewater. It achieves a rapid treatment rate and high pollutant removal efficiency under the action of microorganisms and photocatalytic reactions.	Secondary pollutants are produced. The formation of byproducts is a significant drawback.
Electrochemical destruction	Oxidation using electricity	Sludge is not produced	The high amount of electricity required



Figure 2. Direct discharge of textile effluent into a pond of Rajasthan State of India

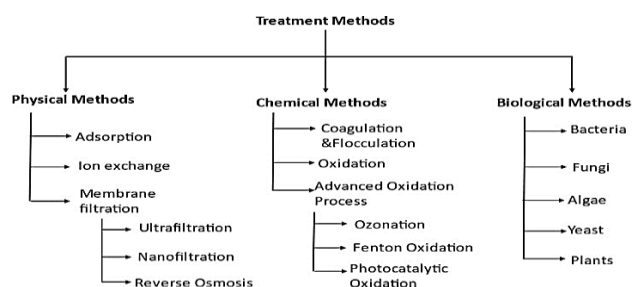


Figure 3. Approaches to treating contaminants from wastewater

MXenens, and aluminum chloride for the remediation of textile effluent (Ihsanullah, 2020). The main advantage is that it is a simple process and aids in eliminating heavy metals (Al-Prol, 2019). Electrocoagulation using aluminum and iron salts or conjugated electrodes of Al/Fe is employed. Still, the drawback of using an inorganic coagulant is that it cannot remove soluble dyes effectively from textile effluent and also leads to the formation of colored coagulates, which impose disposal concerns and generate a secondary level of contaminants (Shah, 2018). Toxicity and TDS levels also increase. Plant-based coagulants, when employed, have proved to be part of sustainable environmental technology. Seed gums of *Ipomoea das Sperma* are competent for decolorizing direct dyes when used with polyaluminum chloride, a conventional coagulant. The coagulation efficiency was also increased for reactive and acid dyes. Polyaluminium ferric chloride, poly ferrous sulfate, and poly ferric chloride are some pre-hydrolyzed coagulants reported to be more effective for decolorizing textile dye wastewater. Flocculation is a mixing stage where unstable particles gently aggregate to structure a floc, which can be discarded smoothly from the suspended solution by sedimentation or filtration. Coagulation–flocculation techniques were effectively applied to decolorize water-insoluble dyes such as sulfur and disperse dyes, whereas they were ineffective for water-soluble dyes (Al-Prol, 2019).

Membrane Filtration

Filtration combines micro, ultra, nano, and reverse osmosis to generate potable water. Microfiltration is not efficient as membrane pores are enormous. Ultrafiltration is done by utilizing a customized membrane composed of 60% styrene-acrylonitrile and 40% poly-vinylidene fluoride content. For the separation and purification of dye solutions, color elimination, and COD reduction are somewhat followed by decreased membrane fouling. Water reuse is made possible by treating ultrafiltration and nanofiltration, which eliminates a few of the drawbacks of the membrane processes,

such as smudging, pore-clogging, and cake formation. Nanofiltration methods significantly reduce COD, removing the dye from the permeate. Using NF and RO procedures, reactive dyes have been effectively eliminated from textile dye waste (Yadav *et al.*, 2022). Membranes make it possible to remove and reuse dyes, supporting chemicals employed in dyeing, and refined water. According to previous studies on dye removal, this method is efficient in getting rid of water-soluble dyes, but membranes are expensive. Another drawback is that fouling occurs due to frequent membrane clogging (Singh *et al.*, 2019).

Ion-Exchange

Color dyes are either primary or acidic; hence, ion exchange resins are generally used for segregation. Agriculture waste such as coir pith, tree barks, sunflower stalks, and banana pith was used as ion exchangers but was not very successful in treating textile effluents for decolourisation. They are ineffective in water for soluble dyes and produce sludge (Shah, 2018).

Adsorption

The elimination and deduction of numerous toxic inorganic and organic compounds from industrial wastewater may be accomplished effectively using adsorption. Textile dye wastewater has been treated or degraded utilising a variety of eco-friendly, economical, and possible adsorbent materials, including *Annona squamosa*, peat, metal oxides, rice husk ash, zeolites, metal-organic frameworks (MOFs), sawdust, *Ananas comosus*, carbon nanotubes, and activated carbon (Khalid *et al.*, 2018; Ihsanullah *et al.*, 2020). BOD, COD, TDS, TOC, and other dangerous recalcitrant coloring pollutants may be eliminated or significantly reduced from textile industry effluent using the adsorption approach. Activated carbon is the robust and most efficient adsorbent element for dissolving various textile dyes. Activated carbon is widely used in the tannery, brewery, and textile industries. It has good removal efficiency, but the limitation is the cost-intensive regeneration process.

Post-treatment disposal of the absorbent is costly and poor at removing numerous contaminants (dyes) from effluent from the textile sector.

Chemical Method

Oxidation

Oxidation for the decolorization by chemical means, oxidizing agents are used. For oxidation, sodium hypochlorite decolorizes water-soluble dyes, whereas water-insoluble dyes are not responsive to chlorine decolorization. Dyes with amino chromophores showed rapid degradation by chlorine treatment. However, the major drawback was the generation of toxic halogenated hydrocarbons, which is hazardous. Oxidizing agent hydrogen peroxide has been used for water-insoluble dyes such as chrome, sulfur, and vat dyes. Also, treatment with hydrogen peroxide decreases COD. The most active oxidizing agent is ozone, which is very reactive and can potentially remove color. Ozone readily decolorizes water-soluble pigments and dyes by breaking the unsaturated bond, and aldehydes, ketones, and organic acids are formed as by-products. Another advantage is that there is zero generation of chemical sludge, and unused ozone gets transformed into oxygen (Yadav *et al.*, 2022).

Advanced Oxidation Process

An advanced treatment method that fastens the degradation of pollutants resistant to conventional oxidation treatment. Hydrogen peroxide and ozone were employed with either catalysts such as Fe, Mn, TiO_2 , etc., or radiations. When UV radiation is coupled with H_2O_2 , it mineralises the dye molecule into CO_2 , water, and other oxides. During this process, hydroxyl radicals are formed, mediating the breakdown of the dye molecules (Shewa and Dagnew, 2020). Catalysts and irradiation enhance the decolorisation of synthetic dyes. Research has reported the role of titanium dioxide, which enhances the degradation rate of azo dyes under UV radiation (Misra *et al.*, 2020). A report of photocatalytic decomposition of textile azo dyes, Direct Red and Acid Orange 7, employing TiO_2 as a photocatalyst for 2 hours in exposure to UV and sunlight. A remarkable decolourisation was 93% and 95%, respectively (Al-Mamun *et al.*, 2019; Adane *et al.*, 2021). Several other parameters, such as catalysts, pH, substrate concentration, and oxidising agents, affect photocatalytic dye degradation. Oxygen, ammonium persulfate, and hydrogen peroxide are used as oxidising agents. Recent developments of different types of photocatalysts are semiconductor-based nanostructures, including doping, polymer-

supported nano complex, magnetic nanocomposites, and heterojunction photocatalysts. Hetero junction photocatalyst can be reused, and the catalytic activity resulted in the range of 90-100% (Ambigadevi *et al.*, 2021). The remediation of refractory contaminants from industrial wastewater has been the focus of advanced oxidation processes (AOPs), which are significant, practical, promising, catalytic, and environment-friendly treatment technologies.

Fenton Reagent

The solution formed by employing H_2O_2 with iron salts Fe (II) as a catalyst is Fenton's reagent for curing wastewater. Fenton's reagent is mainly used for effluent resistant to biological remediation. Kannan *et al.* (2006) and Xu *et al.* (2004) explored the action of Fenton's reagent for treating dye wastewater with or without employing coagulants, flocculants incinerators, and UV lights. Singh *et al.* (2019) reported the decomposition of 20 different dyes such as acid, direct, reactive, vat, disperse, cationic, etc. The major drawback of this method was the demand for high pH and the formation of sludge. When the Fenton reagent was accompanied by UV radiation, then hydroxyl ion radical was formed. This hydroxyl radical plays an efficient role in the decomposition of dyes. Electrochemical techniques have also been conventionally used to remove suspended and dissolved solids, heavy metals, pigments, and dyestuffs from the effluent. These techniques comprise electrocoagulation, electrolysis, electro flocculation, etc. Ferrous hydroxide mediates, eliminating acid dyes from effluent and mineralized azo dyes into aryl amine. The electrochemical methods can remediate up to 90% of the impurities from the industrial effluent, but the technique's limitation is its high energy demand and rapid and uncontrolled reactions (Singh *et al.*, 2019; Sudarshan *et al.*, 2022). The electrolytic process and coagulation are advanced decolorisation methods as the coagulants adsorb the impurities. Aluminum and iron electrodes repeatedly generate polymeric metal hydroxide ions, carrying opposite charges, which help destabilize colloids and thus aid in coagulation (Zhou, 2019). No more chemicals are used in excess in this method, which is why this procedure is a substituted methodology for chemical coagulation for remediating textile and dyeing wastewater.

Biological Treatment

Conventional techniques for eradicating dyes and pollutants are pretty effective, but the sludge formed after the physiochemical treatment imposes a significant disposal problem. Sludge also creates an environmental burden when discharged

untreated, as it constitutes microbial pathogens and organic substances. The conventional techniques have achieved 90-95 % of the BOD removal, but the process is time-consuming and expensive too (Sudarshan *et al.*, 2022). Bioremediation techniques are sturdy due to their versatility and molecular diversity. It is the most efficient alternative to physical and chemical methods; it is eco-friendly, has low operating costs, and generates harmless and non-toxic products. Regular intake of untreated or barely treated noxious wastewater proclaimed carcinogenesis in humans (Sarkar *et al.*, 2017; Bharathi *et al.*, 2022). Almost two decades ago, the biodegradation process was applied to decompose the organic substrates and dyes from the textile effluent wastewater with the help of microbes. So, exploiting microorganisms showing degradative properties became the trend for alleviating water pollution as an eco-compatible alternative (Aktar *et al.*, 2019; Agnihotri *et al.*, 2021). The decomposition of artificial dyes by microbes is a feasible task to exploit but demands a complicated breakdown channel. The rate of degradative performance is entirely dependent on organic matters like dye, temperature, pH of the effluent, the concentration of the oxygen dissolved, and the microbial community available in it. Numerous classified pigments exist in the textile effluent, which is eliminated by different microorganisms like bacteria, yeast, fungi, and algae. This action of microbes can be either aerobic, anaerobic or a combination of both (Sarkar *et al.*, 2017; Agnihotri *et al.*, 2021). During the anaerobic procedures, microorganisms remove the contaminants from the wastewater without utilising oxygen, and in the aerobic process, the availability of sufficient dissolved oxygen to expel the pollutants from the effluent. Bioremediation proficiency depends on the types of microbes and their enzymatic activity. The presence of native microbes and enzymes secreted by them have been isolated and then attempted for dye removal, a significant feature of the textile dye effluent treatment (Aktar *et al.*, 2019).

Degradation by Bacteria

Research on identifying the bacterial strain that can break down textile dyes has begun to work a long time ago, since the 1970s. The isolation of three bacterial strains, *B. subtilis*, *B. cereus*, and *A. hydrophila* degraded textile dye. A variety of aerobic as well as anaerobic bacteria such as *Pseudomonas* sp., *Geobacillus* sp., *E. coli*, *Enterococcus* sp., *Staphylococcus* sp., *Corynebacterium* sp., *Lactobacillus* sp., *Xenophilus* sp., *Clostridium* sp., *Aeromonas* sp., *Acinetobacter* sp., *Micrococcus* sp., *Dermacoccus* sp., *Proteus* sp., *Rhizobium* sp., *Morganella* sp., *Alcaligenes* sp.,

Klebsiella sp., *Shewanella* sp., and *Alishewanella* sp., has been exclusively reported for demonstrating a good result in biodegradation of dyes especially azo dyes which are routinely employed in textile industries (Chantarasiri, 2020; Chaurasia *et al.*, 2022c). Bacteria, *Alcaligenes faecalis* PMS-1, *Enterobacter* sp. EC3, *A. hydrophila* has shown their efficiency for dye decomposition from textile effluent wastewater (Kurade *et al.*, 2012; Barathi and Arulselvi, 2015). *Pseudomonas* sp. is also a widely used strain in the decolorisation of commercial dyes due to its ability to mineralize many of the azo dyes such as Reactive Blue 172, Red HE7B, Reactive Red 22, orange dye I and II. *Enterobacter* sp. F NCIM 5545 has the efficiency to remove Reactive Blue 19 dye from contaminated water (Misra *et al.*, 2020). Textile effluent from a site of Bhilwara, Rajasthan, has been decolourised by native microbes of that affluent and which were identified as *Acinetobacter* sp., *B. cereus*, *Exiguobacterium* sp., by 85%, 72%, and 60% respectively (Kumar *et al.*, 2016). Wang *et al.* (2022) reported the decolourisation of Congo red and Reactive Black 5 and direct black 38 dye by *Enterococcus faecalis* R1107. Mainly, bacterial decomposition is classified into two categories: pure bacterial culture or utilising mixed culture, i.e., consortia. *Proteus mirabilis* LAG degraded Reactive Blue 13 (RB13) dye from textile wastewater has been reported by Awasthi *et al.* (2020). Degradation of malachite green, crystal violet, and brilliant green was observed when inoculated with a culture of *Kurthia* sp. P. rettgeri HSL1 and *Pseudomonas* sp. SUK1 degraded direct red 81, disperse red 78, reactive black 5, and reactive orange 16 (Shah *et al.*, 2012). Five consortia of different *Klebsiella* sp. From 19 strains, decolourised amaranth, tartrazine, sunset yellow, indigo carmine, and quinoline yellow with an efficiency of 96.5% (Poddar *et al.*, 2023). Some microbes showing decolorisation properties have been listed in Table 5. The additional supplements and other physiochemical parameters affect the rate of degradation. So, to fasten the bacterial decolorisation, it is crucial to analyse the factors and the reactors in which biodegradation occurs.

Degradation by Fungi

Like bacteria, fungi also have the potent capability to degrade textile dyes because it has the potential to secrete intracellular as well as extracellular enzymes. Enzymes secreted by the fungi aid in eliminating dyes from the textile effluent. White rot fungi are incredibly potent in decolorization as they release enzymes possessing degradative properties. The extracellular enzyme in the fungal hyphae mineralizes the dye by breaking

Table 5. Biological treatment of textile wastewater and its efficiency

Biological Treatment	Main Characteristics	Microbial Strains	Dyes and Wastewater	Concentration & Conditions	Efficiency	References
Bacterial Bioremediation	Eco-compatible and sustainable, Aerobic/ anaerobic process	<i>B. cereus</i> , <i>E. indicum</i> & <i>A. baumannii</i> <i>A. hydrophilic</i>	Textile dye Wastewater Crystal Violet, Reactive Black 5	Raw; 48hr at 35°C 50 mg/l; 8hr 100 mg/l; 24 hr	82%; 75%; 60% 99 %; 76%	Kumar <i>et al.</i> , 2016 Bhargava <i>et al.</i> , 2018; El-Bouraie, 2018
		<i>B. circulans</i> <i>A. soli</i>	Methyl Orange Reactive Black & Wastewater	50 mg/l; 12hr	99.22%; 98%	Liu <i>et al.</i> , 2017; Khan and Malik, 2018
		<i>Klebsiella</i> sp. & <i>Staphylococcus</i> sp <i>B. aryabhatai DC100</i>	Direct Dye 2B Coomassie Brilliant Blue G-250	50 mg/l; 120hr, 200 ppm 150 mg/l; 72 hr	99% 100%	Desai, 2017 Paz <i>et al.</i> , 2017
		<i>P. extremorientalis</i> BU118	Congo Red	100 mg/l; 24 hr	75%	Neifar <i>et al.</i> , 2016
		<i>Staphylococcus</i> sp. K2204	Remazol Brilliant Blue	150 mg/l; 72 hr	100 %	Velayutham <i>et al.</i> , 2018
		<i>Halomonas</i> sp. strain A55	Reactive Red 184	150 mg/l; 12 hr	96 %	Saha <i>et al.</i> , 2023
		<i>Klebsiella</i> and <i>Enterobacter</i> sp.	Reactive Red Reactive Blue	50 mg/l; 72hr	92%	Chantarasiri, 2020
		<i>Streptomyces</i> sp. S27	Methyl Red	250uM; 120min	99 %	Dong <i>et al.</i> , 2019
		<i>P. occidentalis G1</i>	Acid Red B	50mg/l; 24hr; 120rpm 50mg/l; 16hr; 160 rpm	100 %	Song <i>et al.</i> , 2017
		<i>P. kudriavzevii</i> CR-Y103	Reactive Orange 16	50mg/l; 16hr; 160 rpm	98 %	Rosu <i>et al.</i> , 2018
Mycoremediation (Fungal species)	Biotransformation of pollutants and reduces heavy metals and organic contaminants from wastewater.	<i>Trichoderma</i> sp.	Reactive Orange 16 Congo Red & Methyl Green	100 mg/l; 9 days-	90%; 82%	Ryu <i>et al.</i> , 2017; Argumedo-Delira, 2021
		<i>T. tomentosum</i>	Acid Red 3R	88.5 mg/l; 72 hr	96%	He <i>et al.</i> , 2018
		<i>C. bulleri</i>	Kiton Blue	50 mg/l; 6hr	88%	Vats and Mishra, 2017
		<i>T. villosa</i>	Drimarene Brilliant Blue	20 mg/l;	85%	Singh <i>et al.</i> , 2017
		<i>P. chrysogenum</i>	Direct Black 22	5mg/l/ 3days	COD red	Lanfranconi <i>et al.</i> , 2022
Phycoremediation (Microalgae)	Inhibits coliform growth, lower BOD, phosphorus, and nitrogen, heavy metals, uptake	<i>S. platensis</i> <i>Chlorella</i> sp. KR1, <i>C. vulgaris</i>	Wastewater, Methyl orange, Textile Wastewater		85.6%, 90 %, 97 %	Seo <i>et al.</i> , 2015; Devaraja <i>et al.</i> , 2017; Revathi <i>et al.</i> , 2017
		<i>C. vulgaris</i> PSBDU06 <i>C. vulgaris</i>	Indigo Blue Blue Dye	24 hr 1mg/l	49.03% 63.69%	Sinha <i>et al.</i> , 2016 Ishchi and Sibi, 2020
		<i>Enteromorpha</i> sp.	Acid Red 46	50 mg/l; 30 min 15mg/l; 5 h	96%	Kapoor <i>et al.</i> , 2021
Yeast	Removal of organic contaminants	<i>C. krusei</i>	Basic violet 3 Acid Brilliant Scarlet GR	10mg/l; 1 day	100%	Martorell <i>et al.</i> , 2018
		<i>Sterigmatomyces halophilus</i> SSA-1575 and <i>Meyerozyma guilliermondii</i> SSA-1547.	Reactive Black 5	50 mg/l; 1 day	96.1%	Al-Tohamy <i>et al.</i> , 2023
		<i>T. beigeli</i>	Navy blue HER	300mg/l; 1 day	95%	Khan and Fulekar, 2017
		<i>C. tropicalis</i> TL-F1	Acid Brilliant Scarlet GR	100mg/l; 1 day	100%	Watharkar <i>et al.</i> , 2018
Enzymes	Azoreductase, Manganese Peroxidase (MnP), Tyrosinase Oxidoreductase Oxidoreductase	<i>A. bombycis</i>	Reactive Red	20mg/l; 12 h	92%; 94% COD	Almaamary <i>et al.</i> , 2017
		<i>Candida</i> & <i>Yarrowia</i> spp.	Textile effluent	100mg/l; 3 h	90%	Mendes <i>et al.</i> , 2022
		<i>Meyerozyma guilliermondii</i>	Textile Effluent	100mg/l; 30 h		Li <i>et al.</i> , 2022

Table 5. Biological treatment of textile wastewater and its efficiency

Biological Treatment	Main Characteristics	Microbial Strains	Dyes and Wastewater	Concentration & Conditions	Efficiency	References
Phytoremediation Phytodegradation, Phytoaccumulation Rhizodegradation, Rhizofiltration, Phytotransformation	Parts of plants, such as leaves, roots, etc., absorb nutrients from effluent & thereby lower contamination.	<i>A. densiflorus</i>	Disperse Rubin and industrial effluent	40m mg/l; 48hr	65%,	Almaamary <i>et al.</i> , 2017
		<i>S. grossus</i>	Methylene Blue	200 mg/l; 72 days	86%	Kagalkar <i>et al.</i> , 2015
		<i>B. malcolmii hook</i>	Brown 5R	200 mg/l; 72hr	92%	Chandanshive <i>et al.</i> , 2018
		<i>G. grandiflora</i>	Textile Industry Wastewater	100 mg/l; 72 hr	73%	Rane <i>et al.</i> , 2016
		<i>I. aquatica</i>	Rubine GFL and textile dye effluent Brown 5R	100 mg/l; 72 hr	97%, COD 76%; BOD 82%	Rane <i>et al.</i> , 2016
		<i>S. molesta</i>	Methylene Blue;	200-1000 mg/l; 72 hr	86%	Rane <i>et al.</i> , 2016
Nanobiotechnology (Sustainable bioremediation)	Removal of pollutants by the use of nanomaterials	<i>P. aeruginosa</i> (electrospun nanofibers)	Methylene Blue	Variable concentration	55-70 %	Bilal <i>et al.</i> , 2021
		<i>P. aeruginosa</i> (Zirconia NPs)	Tetracycline	526 mg/g	90%; 80%	Rodríguez <i>et al.</i> , 2020; Gül, 2018
		<i>P. ostreatus</i> (Enzyme immobilized NPs)	Bisphenol; Industrial Effluent			
		<i>Actinomycetes</i> (Silica NPs)				

the bond of the complex compound and then adsorbing it on its surface. Laccases, Lignin peroxidase (LiP), and manganese peroxidase (MnP) are some of the fungal enzymes that mediate the breakdown of dyes (Lade *et al.*, 2016; Patel *et al.*, 2022). Lichen *Permelia Peralta* was found to show its efficiency in decolorizing a dispersed dye, Solvent Red 24. *A. Niger* eliminated Remazol Brilliant Blue R (RBBR) and Acid Red 299 (NY1) (Saroj *et al.*, 2015). Benghazi *et al.* (2014) reported that *Penicillium oxalicum* SAR-3 decolorised azo dyes- acid red 183, direct red 75, and direct blue 15. Hadibarata *et al.* (2013) reported *Pleurotus eryngii*, a white rot fungus degrading naphthalene dye. Strains like *Magnusiomyces* and *Candida* detoxified azo dyes. A few other examples are mentioned in Table 5. The drawback of employing white rot fungi to remove dyes from wastewater is that it requires nitrogen deficit conditions, a large reactor size, a prolonged growth phase, and unpredictable enzyme synthesis. The exploitation of fungi is recommended for only a few days because, after some days, when bacteria start growing, fungi will not be able to be more functional to degrade dyes (Shewa and Dagnew, 2020).

Degradation by Algae

Bioremediation by algae is also known as phytoremediation. It is commonly found on lakes, ponds, ditches, and rivers. The breakdown of dyes mediated by algae follows three working systems: 1) consuming dyes as a food source for growth, 2) transforming dyes to intermediate products or CO₂ and H₂O, and 3) chromophores adsorption on an algal wall. Biosorption and biodegradation are

distinct techniques for removing dyes (Garg and Tripathi, 2017). Biosorption signifies the aggregation of dye molecules on the walls of algae, while biodegradation implies the breakdown of dye molecules with the help of enzymes released by algae. *Enteromorpha sp.*, a green microalga, mediates the degradation of Basic red 46 dye at 25°C in 5 h. *Shewanella* decolorized acid red 27 when mixed with sodium chloride. Several algae have been reported to degrade a variety of dyes. *Cladophora*, *Cosmarium sp.*, and *Vaucheria* species mediate in removing malachite green, *Stoechospermum marginatum*, a brown alga decolorised acid orange II, *Spirogyra* decolorising azo dye, reactive yellow 22 by adsorption (Shewa and Dagnew, 2020; Agnihotri *et al.*, 2021). Some more decomposition of dyes by algae is listed in Table 5.

Degradation by yeast

Yeasts are unicellular, rapidly multiplying organisms like bacteria and can survive in adverse environmental situations (Garg and Tripathi, 2017). However, at low pH, yeast performs better in decolourising azo dyes. Das and Charumathi (2012) mentioned *Saccharomyces cerevisiae* MTCC-463 to decolorise Malachite Green and Methyl Red dyes. *Trichosporon beigeli* NCIM-3326 has the potency to decolorise Navy Blue HER (Bhatia *et al.*, 2017). Meehan *et al.* (2010) reported *Kluyveromyces marxianus* IMB3 to decolorize Remazol Black-B dye up to 98%. *Candida oleophila*, *C. albicans*, *C. tropicalis*, and *Issatchenkia occidentalis* were very effective in the enzymatic deterioration of azo dyes.

Mechanism of dye degradation by enzymes

The optimum outcome of biodegradation is a substance's mineralization, or total degradation, through its breakdown into the water, carbon dioxide, and an inorganic end product (Sarkar *et al.*, 2017). Previous investigations made it possible to employ microorganisms' metabolic capacity to break down or change organic pollutants into materials that are innocuous to the environment. Both external and intracellular actions were possible for these enzymes. These enzymes have also been found in fungi, plants, and other sources than bacteria. Fungi are a fantastic source of enzymes that break down the color. With the requirement of less expensive culture, maintenance costs, downstream processing, and other factors, microbial enzymes offer significant benefits over alternative sources. Enzymes can be used to treat textile effluent since they have a broad range of substrate specificity, are quickly immobilized by nature, and are highly effective (Chang *et al.*, 2021). Enzymes, specifically azoreductase and laccase, appear to offer the most promise for the enzymatic breakdown of commercial azo dyes. Under unfavorable circumstances, oxidase and peroxidase enzymes are engaged in other metabolic processes and can potentially partially destroy the azo dye. Bacterial decolorisation usually begins with an aerobic or anaerobic process or a sequential technique, followed by reductive breakage of the -N=N- bond. Azo dyes comprise numerous additional electron-withdrawing groups and the (N=N) chromophore group, which is an electron deficit (Sarkar *et al.*, 2017). Anaerobic processes break down azo dyes into a colorless, naturally carcinogenic amine, which is then broken down by aerobic processes. When aromatic amine generated in a microaerophilic environment is further broken down in an aerobic environment, sequential microaerophilic or aerobic procedures can be employed (Ajaz *et al.*, 2020).

Azoreductase is a reducing enzyme that uses a reductive cleavage method to break down azo dye into colorless amines. It needs an electron donor in the form of a redox reaction, such as a low molecular weight-reducing equivalent like FADH or NADH. This enzyme can be classified into one of three groups based on its coenzyme: it uses only NADH, NADPH, or both. Azoreductase may be membrane- or cytoplasmically bound. The biotreatment method for azo dye-containing wastewater must take into account microbial azoreductase. Due to the complicated chemistry of some commercial azo dyes, cytoplasmic azoreductase's role in decolourisation has been questioned since it is difficult to diffuse through a cell membrane (Ajaz *et al.*, 2020). Even though some dyes cannot be

broken down effectively, enzymes are helpful in textile water pretreatment due to their substrate specificity.

Factors Affecting Dye Decolorization

Various parameters impact the efficacy of biological treatment systems. Optimization of the supply of oxygen, pH, temperature, and redox potential enhances the textile effluent treatment. Some chemical compounds might act as inhibitors of dye decolorization (Srivastava *et al.*, 2022).

Oxygen

Oxygen may hinder the dye reduction pathway if the extracellular environment is aerobic during the dye reduction stage, as it acts as a high-redox-potential electron acceptor. This is because the cells preferentially utilize the electrons released by the oxidation of electron donors to reduce oxygen rather than the azo dye.

Dye Structure and Concentration

While color removal is more challenging with extensively substituted, high molecular weight dyes, it occurs more frequently in dyes with simple structures and low molecular weights. Hydrogen bonding and the density of electrons around the azo bond significantly influence the reduction rate.

Moreover, the time needed to remove the color increases with the dye concentration. From one of the reports, 1-10 mM concentrations were readily decolorized, but color removal decreased as the dye concentration grew to 30 mM.

pH

The rate of color removal tends to drop quickly at highly acidic or strongly alkaline pH values. Colour removal works best at a neutral or slightly alkaline pH value. As a result, the colored effluent is frequently buffered to improve the cell culture's ability to remove color. The formation of aromatic amines also increases the pH value.

Temperature

At high temperatures, dye decolourisation drops because of the loss of cell viability or can lead to enzyme denaturation (Srivastava *et al.*, 2022).

Phytoremediation

Phytoremediation of contaminated water exploits the capability of plant roots to imbibe the nutrients from wastewater, lowering the level of poisonous chemicals. It incorporates phytodegradation, phytoaccumulation, hemofiltration, biodegradation, and phytotransformation. Phytoremediation is a process of extraction of contaminants and heavy metals

from the wastewater, groundwater, soil, and sludge from the ecosystem by plants. Macrophytes, categorized as submerged or floating plants, are aquatic plants that develop near the water's vicinity or in the water body (Manjounath and Kousar, 2016). Research to investigate the potential of some macrophytes for removing heavy metals at varying concentrations. Macrophytes are biological monitors for measuring the metal strength and their ability as biofilters of the aquatic ecosystem. Pistia stratiotes removal of dark blue to light and heavy metals as well, Azolla pinnata reduction of physiochemical parameters, Salvinia molesta, Eichhornia crassipes, Spirodela polyrrhiza (Chandra *et al.*, 2017).

Treatment by Microbial Fuel Cell

Microbial fuel cell (MFC) is a biological process that is used to convert chemical potential energy (organic compounds in wastewater) into electric power by the application of various oxidation-reduction reactions (Shewa and Dagne, 2020). Microbes employed in the MFC oxidize the organic matter in the water to generate protons and transfer them from anode to cathode for oxygen consumption. In the anode chamber, anaerobic bacteria degrade pollutants into carbon dioxide, forming electrons or protons. Also, less activated sludge is produced than other techniques (Ilamathi and Jayapriya, 2018). The drawback of MFC is that this method cannot be applied to large-scale industries as the investment cost is high and power generation is also low. Some investigations to increase the efficiency of power generation by MFC have already been in progress. In past years, activated or modified carbon nanofibers have been used for the anode instead of high-priced fragile electrodes. But, because of internal resistance, it offers some limitations. Nanotube systems enhance energy and balance and decrease charge transfer resistance. Most carbon substances are used for anodes of various metals, including Ni, Cu, TiO₂, and Si, which can lessen inner resistivity. Thus, using carbon composite material alongside low-value electrocatalyst materials like Cu and TiO₂ has promising anode fiber, whilst similar research is needed to be implemented in this way. Recent studies centered on cathode elements and using nanofibers or carbon nanotubes to increase surface proficiency. It has additionally been suggested that Co₃O₄ (tricobalt tetroxide)/ nanocarbon composite substance plays an equal role of Pt/C in all components, which include energy density, present-day at discount peak, and coulombic efficiency (Song *et al.*, 2015). Thus, low-value catalysts, including cobalt, manganese dioxide, iron, etc.,

have an effective cathode substance for nanofiber composites. More efforts are needed to do in this field. Sonu *et al.* (2020) reported that the COD value was 82.14 % reduced, 68 % reduction in TDS value, and 74.8 % dye wastewater decolorisation using microbial fuel cells. Instead of using expensive chemical, physical, or advanced oxidation procedures, toxic wastes can be biotreated in MFCs. As reported, sulfate-reducing mixed communities in an anodic MFC chamber generated electricity, degraded dye, and reduced sulfate simultaneously (Miran *et al.*, 2018).

Multi-omics

The term OMICs means the holistic approach to the assessment and quantification of biomolecule repositories responsible for microbial physiology and metabolism, structure, and dynamics through various techniques such as genomics, proteomics, and metabolomics (Chaurasia *et al.*, 2022b). Omics study has the potency to evaluate the genetic diversity of microbes in the environment and analyze the genes responsible for the breakdown of the pollutants. The omics technique simultaneously correlates biomolecules such as DNA sequences, mRNA, proteins, and secondary metabolites from individual organisms and the microbial community (Gutierrez *et al.*, 2018). It gives a more precise and more detailed picture of bioremediation and eco-sustainability. Metagenomics is applied to study the whole genome and its sequences and how genes are regulated in an anthropogenic environment. Metagenomics interprets the microbial population from the contaminated sites. Transcriptomics is applied to find out the mRNA expression. Meta proteomics is that branch that can be used to study the proteins from polluted areas. Metabolomics examines the proteinaceous primary and secondary metabolites synthesized by the microorganisms during a specific environmental condition (Chandran *et al.*, 2020). Figure 4, depicts the steps involved in the multi-omics approach. Multi-omics strategies are generally mentioned to look at microbial groups because a single omics evaluation cannot expose the activities of the microbial community. It has been validated to include new techniques for green bioremediation methodology. Omics strategies have the efficiency to assume microbial metabolic pathways in contaminated environments. These high-throughput analyses could be valuable resources in monitoring novel microorganisms for a holistic approach to bioremediation and offer an exceptional and unique vision of their vital biological pathways of degradation on the molecular level (Rodríguez, *et al.*, 2020).

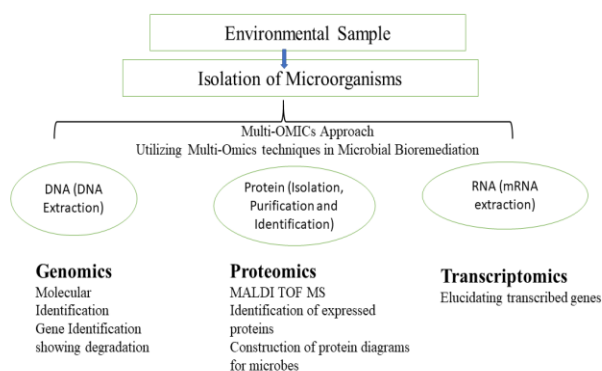


Figure 4. Screening and identification of microbial biota using a multi-omics approach

Combined Strategies

The gradual increase of dyes and wastewater containing dyestuffs endangers human health and the environment. The treatment utilizing a single treatment does not satiate regulatory requirements due to the dye's refractory nature and the continual changing of the effluent properties. Numerous authors have also emphasized that due to stricter rules surrounding the disposal of dye wastewater, adopting a single treatment process is no longer practical in the modern era. Several colors, heavy metals, and other substances are present in the effluent from the businesses, making removing them with a single treatment altogether impossible. The complexity of industrial wastewater makes dye removal from a single treatment highly difficult and time-consuming. By combining several strategies according to the needs, the shortcomings of a single treatment method may be avoided without yielding beneficial outcomes. The steady rise in dyestuffs and wastewater containing dye causes environmental degradation and health problems (Sarkar *et al.*, 2017). The distinction between integrated and hybrid processes must be made explicitly since they might be mistaken for one another. An integrated process is one or more treatments that can be administered in succession. Hybrid processes, on the other hand, are those in which two treatment processes are combined into a single treatment process (Kadri *et al.*, 2022). For example, Bahmani *et al.* (2013) developed a Fenton-biological process, decolorizing Reactive Black 5 within 60 h. A combination of advanced oxidation and biological techniques could remove and reduce 99% of Acid Red 18, 97% of COD, and 87% of phosphorus from textile wastewater (Azizi *et al.*, 2015). Han *et al.* (2016) developed a novel combination of forwarding osmosis and coagulation/flocculation to treat industrial wastewater. A hybrid of membrane bioreactor and reverse osmosis method was found to be very

efficient in the removal of color and reduction of various parameters like BOD, COD, and TDS from textile wastewater (Ali *et al.*, 2016). Hamad and Said (2021) reported that immobilised *A. niger* could be exploited as an efficient adsorbent for removing Congo red dye from wastewater. Qamar *et al.*, (2020) enhanced chitosan adsorbents into nanostructures and showed high adsorption efficiency towards various dyes and dyestuff.

In principle, the multidisciplinary approach reduced the cost and resources to complete the degradation of dyes (Liu *et al.*, 2021). The removal of various other contaminants from municipal wastewater, domestic oil wastewater, pharmaceutical wastewater, tannery wastewater, hospital wastewater, and poultry slaughterhouse wastewater has recently attracted a lot of interest due to the use of hybrid materials or processes to improve the results (Chaurasia *et al.*, 2019). The researchers are assisted in applying the combinations more accurately for the dye removal treatment by combining hybrid procedures used in the standard approach to remove textile dyes. Several research for the removal of dyes have been described in which diverse physio-chemical methods combine with biological processes for the decolourisation and degradation of a variety of recalcitrant coloring pollutants, and various environmental parameters such as BOD, COD, TOC, and TDS were found to be more sustainable approach (De-Luca *et al.*, 2021; Bilal *et al.*, 2021).

Treatment of wastewater to recycle, collect, and reuse the "treated" effluent and ensure no wastewater discharge to the environment. A ZLD system uses a variety of modern wastewater treatment technologies. CETP is developed in significant industrial clusters or large-scale companies across India to achieve ZLD. A typical ZLD is a multi-component system comprising three main components: a Pre-treatment Unit (Physio-chemical, Chemical, and biological), Reverse Osmosis (Membrane Processes), and

evaporator and crystallizer (Thermal Process). The circular economy will enable a general greening of value chains and business processes. These adjustments save costs and increase the company's resistance to external shocks (Brydges, 2021). The circular economy is a regenerative system where waste is eliminated and materials and energy move in closed loops. In such a system, all materials are recycled, utilized again, or put to good use. Goods and services are created in a way that makes recycling and repurposing simple.

Future Prospect

The laboratory results in the microbial efficiency of dye degradation are very approachable. However, some features must be improved so that the bioremediation method can be further implemented for pilot, commercial, and industrial-scale production.

- The degradation pathway will be affected by Experiments on the responsible microbes, factors, and polluted sites.
- Implementation of bioreactors and cost management.
- Techniques optimization from lab to pilot and further to industrial scale.
- Using pure culture or consortiums of potent microorganisms in treating raw effluent requires extensive research to determine their commercial viability.
- Providing new sustainable solutions for companies to treat their effluents using pellet or powder form of microbes.
- Microorganisms can adapt varied strategies, and genetic engineering is an alternative to degraded dyes. To identify the genes responsible for dye degradation.
- An investigation on the by-products formed after the bioremediation can be used as a source of nutrition, such as animal feed.
- Strict action by local legislation for effluent treatment and disposal.

Conclusions

Most of the previous studies depict the chemical complexity of wastewater, leading to environmental pollution. Our review paper suggests a holistic approach toward eco-sustainability based on developing inexpensive, eco-friendly methods. Combined strategies based on physiochemical and biotechnological processes for treating the dye effluent have proven to be a proactive method. Future research should focus more on dealing with consortia-based bioremediation, which might be an

eco-friendly approach to sustainable development. The present review also suggests the multi-omics approach for screening and identification of microbial consortia from the native ecosystems.

There must be an industry standard with precise instructions on using and disposing of chemicals (amongst other things). We suggest that industry stakeholders impose strict rules to comply with CTEP, even in small-scale industries, for zero liquid discharge rules. The government should frame strict regulations to check zero discharge protocol by the concerned sector. The suggestion is also for the MSME to follow environmental laws and regulations to minimize synthetic dyes, water, and energy, leading to various forms of pollution. Industries can reutilize the water and chemicals as raw materials for themselves and other sectors after-treatment effluent. In the future, treated water shall be employed for domestic purposes such as washing and irrigation.

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