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Review on: Biological Textile Dye Degradation for Sustainable Wastewater Treatment

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Abstract : **The textile industry is a major contributor to chemical pollution due to its heavy use of complex chemicals and water during textile processing. The use of microorganisms for environmentally friendly textile effluent treatment is gaining importance, including bacteria, white rot fungi, and algae. Dyes contain chromophores and auxo chromes responsible for their substance and color. Textile dyes contribute to environmental pollution and health risks due to their high thermal and photostability. Biological treatment methods offer promising solutions for addressing dye pollution in wastewater, providing sustainable and environmentally friendly alternatives to traditional treatment approaches.**

Key words—**Textile dye, contaminated sites, environmental pollution, biodegradation, dye decolorization.**

Introduction:

The textile industry, one of the largest contributors to chemical pollution, heavily uses complex chemicals and water during textile processing. Untreated and unused wastewater, high in pH, color, and lethal compounds, is released as wastewater. This untreated wastewater mixes with freshwater resources, increasing water pollution and affecting aquatic biota. The industry's extensive use of chemicals contributes to environmental degradation [1][2]. Textile industry effluents are complex chemical substances, including organochlorine-based pesticides and heavy metals, that are crucial components of various dyes used in fabric dyeing processes [3].

The fabric industry discharge poses a significant ecological issue, as eradicating dyes from textile waste is challenging. Proper treatment processes are needed to release effluents into the environment without compromising environmental health [4][5]. Frequent exposure to textile dye effluents poses a significant health risk, potentially leading to various health issues such as suppression of immunity, autoimmune diseases, respiratory complications, blood circulation issues, damage to the central nervous system, allergic reactions, cancerous diseases, vomiting, diarrhea, tissue damage, eye skin disorders, eye infections, and lung-related problems [6].

The use of microorganisms for environmentally friendly textile effluent treatment is gaining importance. Some microbes, including bacteria, white rot fungi, and algae, can break down and absorb many textile dye effluents, making them easier to remove from the environment [35]. This trend is particularly significant for complex-colored compounds that are difficult to remove from the environment [7].

Different bacterial strains can mineralize, decolorize, and degrade various dyes under specific conditions. This has led to increased interest in disintegrating textile dyes. Bacterial oxide reductive enzymes, such as laccase and azo reductases, play a crucial role in dye decolorization, particularly in azo dye color removal [40]. These enzymes catalyze the cleavage of azo bondages, allowing for the development of effective, biodegradable methods for textile effluent management. This research highlights the potential of bacterial azo-reductase enzymes in this process [8].

Enzymes are biochemical means for effective wastewater treatment, targeting specific pollutants without affecting other components. They can be used intracellularly and extracellularly, and yeast can decolorize dyes and survive in hostile conditions.

Biosorption, the uptake of chemicals by microbial mass, is also useful, with algae, yeast, filamentous fungi, and bacteria being examples of microbes that eliminate dyes through biosorption processes [9].

TEXTILE DYES

Dyes are coloring substances used to add color to substances or modify their color. They contain chromophores and auxo chromes responsible for their substance and color [43]. Textile dyes are mostly synthetic chemical compounds with an aromatic structure, which can decrease light penetration and disrupt photosynthesis in aquatic ecosystems. Most dyes used in the textile industry are synthetic, extracted from coal tar and fossil fuel intermediates. They are sold in powders, granules, pastes, or solvent dispersions. The latest dyes are formulated to meet new technology needs, fabric styles, detergents, and environmental concerns [33]. Seasonal demand and variations affect the demand for these dyes. Industrial textile dyes must expand to meet modern and unique technological specifications. The trend of using these dyes is rapidly changing, ranging from durable synthetic fibers to high-cost cellulosic fibers [10].

TYPES OF DYES AND THEIR PROPERTIES

The classification of dyes is dependent on various parameters, as shown in Figure 1.

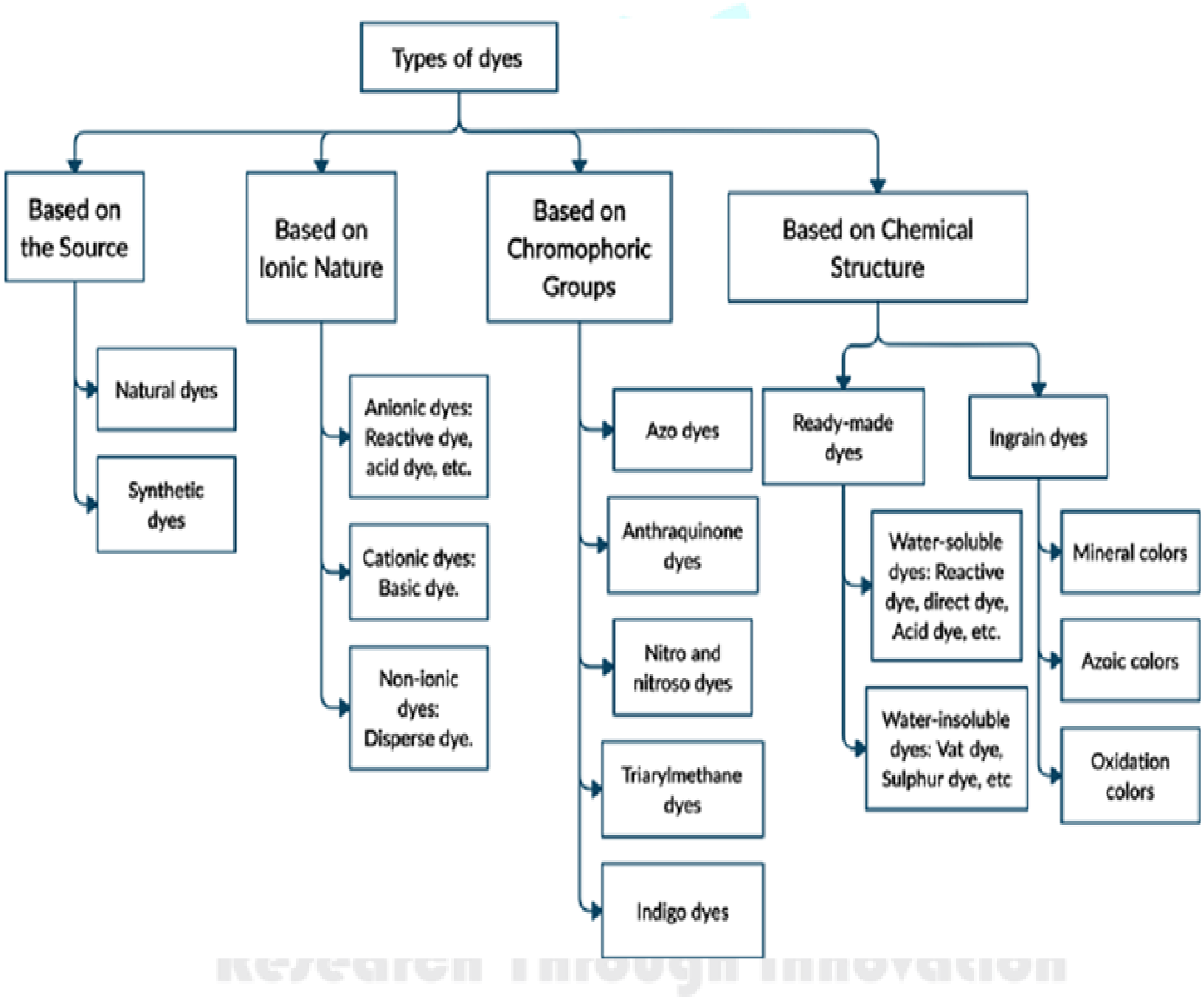

Fig. 1. Classification of dyes - El Harfi, S., & El Harfi, A. (2017). Classifications, properties and applications of textile dyes: A review. Applied Journal of Environmental Engineering Science, 3(3), 311-320.

- ***Direct Dyes****:*

Direct dyes are dyes that can be added directly to fabric due to their good affinity. They are predominantly sodium salts of sulphonic acid or carboxylic acid, with azo as their leading chromophoric group. They are soluble in water and anionic, commonly used to color cellulosic and protein fibers. However, they produce a wide range of wastewater during the dyeing process [12].

- ***Reactive Dyes***

Reactive dyes, containing halogen-containing reactive groups, form a covalent bond with fabric fibers, making them ideal for dyeing cotton fabrics. They are soluble in water and anionic, with strong wash fastness and a covalent bond, making them less responsible for wastewater production. They can also be used to dye protein and polyamide-based products [34].

- ***Basic Dyes***

Organic-based salts with cationic charges are used for color production. Solubilized in methylated spirit and alcohol, but not water, they are primarily used for acrylic and jute-related goods [37].

- ***Vat Dyes***

Vat dyes, composed of a keto group, are water-soluble by vatting and are used to dye denim or jeans. They require alkaline conditions for vatting, making them suitable for cotton-based goods [63].

- ***Disperse Dyes***

Dyeing thermoplastic hydrophobic fabrics with synthetic dyes is done, but these dyes are not water-soluble and have little fiber attraction. They are replaced by azo, anthraquinone, or diphenylamine compounds, mainly used for dyeing acetate, triacetate, nylon, acrylic, and polyester-related goods [64].

- ***Acid Dyes***

Acid dyes are carboxylic salts soluble in water and anionic, forming ionic bonds and van-der-Waals and H-bonds. They are effective on polyamide and protein fibers and are used for dyeing protein fibers and polyamide-based products. Acid dyes are water-soluble and can be used for thermoplastic hydrophobic fabrics [65].

- ***Azoic Dyes***

These dyes are mono or bi-azo water-insoluble coloring substances that require coupling components to produce colors. They are not ready-made and require two baths for preparation. Their color is influenced by diazonium and coupling compounds, making them versatile in textile industries. Common materials used include cotton, nylon, and polyester [69].

- ***Mordant Dyes***

Chrome dyes, primarily composed of inorganic chromium, are used for dyeing natural protein fibers, nylon, and modacrylic fibers, as they stick to fibers with chemical binding agents called mordants [70].

- ***Sulfur Dyes***

The sulfur dye, similar to vat dyes, is used for producing black and brown cotton fabrics. It requires reducing agents and oxidation in an alkaline medium. Generally used for silk, paper, leather, and cellulosic materials [53].

- ***Anthraquinone Dyes***

Textile dyes, including anthraquinone and azo dyes, cover the most visible spectrum and have long-lasting degradation resistance due to their glued aromatic structures [75].

IMPACT OF INDUSTRIAL DYES ON HUMAN HEALTH AND ENVIRONMENT

- ***Environmental Effects***

Textile dyes pose significant environmental pollution and health risks due to their high thermal and photo-stability [39]. The primary environmental issue is the absorption and reflection of sunlight entering water, which can lead to soil degradation and disruption to flora and fauna. Azo dyes, a major class of synthetic dyes used in the industry, are highly electron-deficient and exhibit carcinogenic signs of reductive cleavage [13]. They can change soil properties, degrade water bodies, and cause disruption to aquatic life. The poisonous nature of dyes leads to soil microorganisms dying, affecting agricultural productivity. The presence of a minimal amount of azo dye in water affects aesthetics, transparency, and water-gas solubility. Reducing light penetration by water lowers photosynthetic activity, induces oxygen depletion, and deregulation of aquatic biota's biological cycles. Most azo dyes are toxic to the environment and mutagens, causing severe chronic effects on animals [40]. The long-term presence of dyes in the environment can lead to toxic effects on aquatic ecosystems, including accumulation in sediments and decomposition of contaminants in carcinogenic or mutagenic compounds [14].

- ***Effects on human***

1,4-diamine benzene, an aromatic amine, can cause skin irritation, contact dermatitis, chemosis, lacrimation, exophthalmos, lifelong blindness, rhabdomyolysis, severe tubular necrosis, vomiting, gastritis, hypertension, and vertigo [15]. Ingestion can cause edema and respiratory distress. Aromatic amines can be stimulated by water, facilitating absorption through the skin and mouth. Water-soluble azo dyes become risky after liver enzyme metabolism [49]. Exposure to wastewater, particularly from the unavailability of fresh canal and subsoil water, can lead to symptoms like plaque in teeth, knee pain, and grey hair in irrigated crops [16].

THE TEXTILE INDUSTRY EFFLUENTS.

The textile industry uses chemicals like dyes, pigments, and aromatic compounds for various applications, including dying, tanning leather, and coloring [17]. However, these chemicals also contribute to environmental pollution, with untreated effluents posing serious threats to human health, aquatic life, domesticated animals, and livestock [41]. Out of the 0.7 million tons of dyes produced annually, around 200,000 tons of resistant compounds are lost annually due to faulty dying processes [18]. Despite their high resistance to physical, chemical, and microbial degradation, these compounds remain in the environment, posing a threat to the environment and flora and fauna [19].

TREATMENT METHODS FOR TEXTILE EFFLUENTS

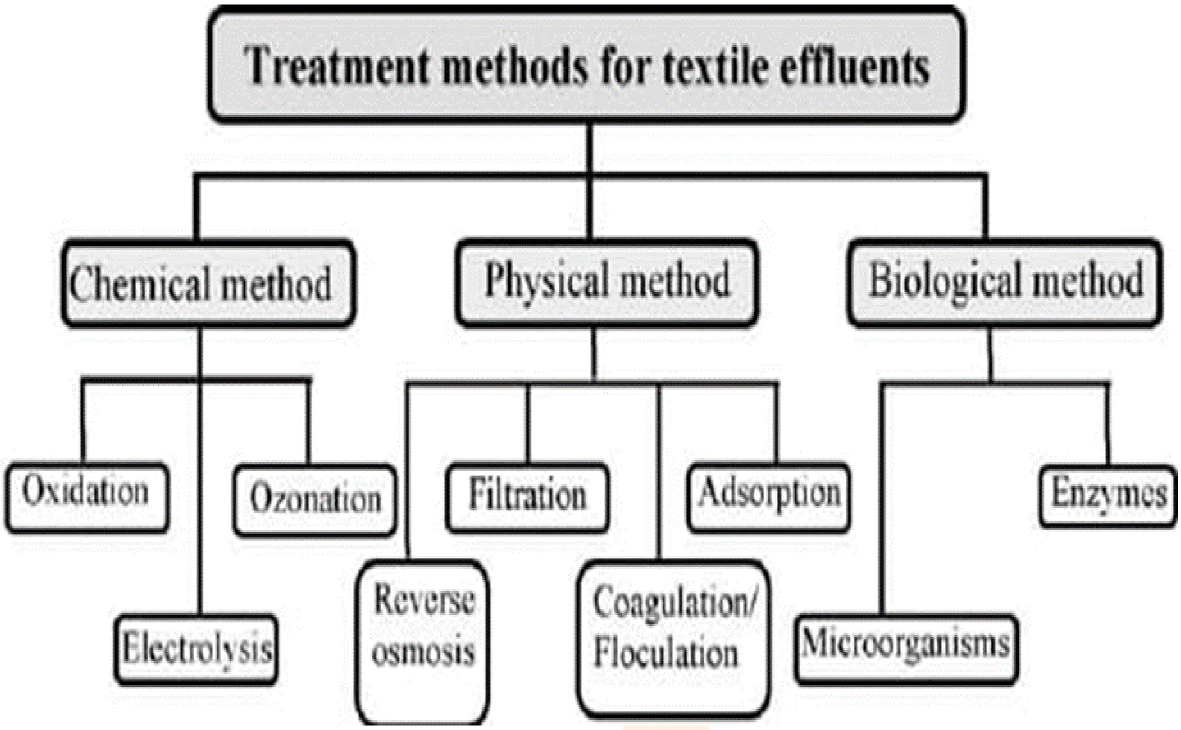

Fig.2. Treatment methods of textile effluents [20]

- ***Physical Treatment***

Textile manufacturing facilities use physical methods like ion exchange, adsorption, and irradiation for treating wastewater due to their high dye removal potential and low operating costs [21]. Adsorbents like activated carbon, coal, silica, wood, clay, agriculture wastes, and cotton waste are used in dye effluent treatment processes [22]. Irradiation is suitable for low-volume decolorization but requires high dissolved oxygen for dye degradation. Ion exchange has limitations as it is specific to dyes and other impurities in wastewater, reducing the process's capability. Overall, these methods are widely used in the industry for effective wastewater treatment [23].

- ***Chemical Treatment***

Physical methods cannot completely remove color from textile effluent due to the need for additional processing and increased treatment costs [24]. Chemical treatments, such as flocculation and coagulation, are often used to remove organic contaminants. Coagulation-flocculation is the most common technology used in textile wastewater treatment plants in developed nations. This method can be used pre-, post, or as the primary form of treatment [25]. Although soluble pigments in textile wastewater do not dissolve as efficiently as insoluble colors, coagulation techniques can effectively remove mostly sulfur dye and disperse dyes. Filtration techniques like reverse osmosis, ultra-filtration, and nano-filtration are used for reusing water and recovering chemicals in the textile sectors. These techniques apply to both filtering and recycling in the textile sectors [26].

- ***Biological treatment***

• Activated Sludge Process: Uses aerobic microorganisms to biodegrade organic pollutants, including dyes, in wastewater [53].
• Biological Aerated Filters (BAFs): Degrade dye molecules by microorganisms growing on the filter medium [42].
• Combined Treatment Systems: Combine multiple processes for comprehensive removal of dye contaminants [43].
• Advanced Membrane Processes: Remove dye molecules and contaminants from wastewater through semi-permeable membranes [53].

Biological treatment of dye wastewater:

Biological treatment of dye wastewater typically involves the use of microorganisms that can metabolize organic compounds, including dye molecules, as a carbon and energy source. Some of the common microorganisms used in biological treatment systems for dye wastewater include [43].

Table 1 Microorganisms responsible for textile dye degradation

Microorganisms	**Dye**	**Reference**
Bacillus cereus	Malachite green	[28]
Pseudomonas spp	Phenol Red	[29]
Bacillus subtilis	Acid Blue 113	[29]
Geotrichum spp	Reactive black 5 & Reactive red 158	[30]
Saccharomyces cerevisiae MTCC46	Methyl Red	[31]
Spirogyra rhizopus Cosmarium spp	Acid Red 247 Triphenylmethane & Malachite green	[32]

Biofilm-Forming Organisms:

Some biological treatment systems utilize biofilms, which are communities of microorganisms attached to a surface, to enhance the degradation of organic pollutants. Biofilm-forming bacteria and fungi play a crucial role in biofilm-based treatment processes such as biological aerated filters (BAFs). and trickling filters [33].

Genetically Engineered Microorganisms (GEMs).:

Researchers have explored the use of genetically modified microorganisms with enhanced capabilities for degrading specific pollutants, including dyes. GEMs can be engineered to produce enzymes or metabolic pathways tailored for efficient dye degradation [34].

FUTURE DIRECTIONS FOR BIOLOGICAL DYE DEGRADATION:

Microbial Consortia Engineering:

• Optimizing microbial consortia for enhanced dye degradation.
• Selecting and engineering microorganisms with complementary metabolic pathways.
• Employing genetic engineering techniques to enhance performance and stability.

Bioreactor Design and Optimization:

• Emphasizing improved mass transfer, substrate availability, and microbial growth conditions.
• Exploring advanced reactor configurations for higher treatment capacities and reduced footprint.

Bioaugmentation and Bio stimulation:

• Developing strategies for bioaugmentation and bio stimulation to accelerate dye degradation rates and improve treatment performance.
• Applying tailored microbial inoculants or optimizing environmental conditions.

Metagenomics and Systems Biology:

• Employing metagenomic approaches to characterize microbial communities in dye-contaminated environments.
• Using systems biology approaches to design effective bioremediation strategies.

Bioremediation in Complex Environments:

• Addressing challenges in complex environments like industrial wastewater, soil, and groundwater.
• Developing strategies for remediation of mixed dye pollutants and co-contaminants.

Integration of Biotechnologies:

• Exploring the integration of biological treatment methods with other biotechnologies to enhance dye degradation efficiency.

CHALLENGES:

The future of biological dye degradation faces several challenges, including the complexity of dye structures, treatment efficiency and rates, microbial adaptation and stability, co-contaminants and complex environments, scale-up and engineering challenges, resource limitations and technological barriers, regulatory compliance and public perception, and economic viability and market adoption. Dyes used in various industries have diverse chemical structures, making it difficult to optimize microbial degradation pathways for effective treatment. Managing substrate availability, microbial activity, and environmental conditions is crucial for achieving high treatment efficiency and rapid degradation rates. Addressing co-contaminant removal and bioremediation in complex environments is essential for comprehensive wastewater treatment. Overcoming resource limitations and technological barriers is crucial for global progress in wastewater management.

CONCLUSION:

In conclusion, biological treatment methods offer promising solutions for addressing dye pollution in wastewater, providing sustainable and environmentally friendly alternatives to traditional treatment approaches. Continued research and innovation in biological dye degradation hold the potential to revolutionize wastewater treatment practices and contribute to a cleaner and healthier environment.

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