Biosorption and bioremediation of wastewater of textile origin: A sustainable solution for the industry.

Biosorción y biorremediación de aguas residuales de origen textil: Una solución sostenible para la industria.

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Review article

***Abstract*— Today, the textile industry stands out for its global economic contribution. However, its expansion brings growing concern due to environmental impact and massive generation of highly polluted wastewater. These waters, originating from the textile industry, host a wide range of harmful organic compounds, including dyes, persistent chemicals, heavy metals and other elements, representing a significant environmental challenge and a significant risk to aquatic ecosystems and human health. This article focuses on the application of bioremediation and biosorption as essential methods to address the problem of water pollution from the textile industry. These methods have emerged as promising and sustainable solutions to this growing concern, offering significant progress in water pollution mitigation and a hopeful outlook for the sustainable development of the textile industry. Its proper and continued implementation can lead to more responsible and environmentally friendly practices to degrade and eliminate pollutants using microorganisms effectively.**

***Index Terms*— Bioremediation, Biosorption, Contaminants, Textile industry, Wastewater.**

***Resumen*— En la actualidad, la industria textil destaca por su contribución económica a nivel mundial. No obstante, su expansión conlleva una creciente inquietud debido al impacto ambiental y la generación masiva de aguas residuales altamente contaminadas. Estas aguas, provenientes de la industria textil, albergan una amplia gama de compuestos orgánicos nocivos, incluyendo colorantes, sustancias químicas persistentes, metales pesados y otros elementos, representando un desafío ambiental considerable y un riesgo significativo para los ecosistemas acuáticos y la salud humana. Este artículo se enfoca en la aplicación de la biorremediación y la biosorción, como métodos esenciales para abordar la problemática de la contaminación del agua derivada de la industria textil. Estos métodos han surgido como soluciones prometedoras y sostenibles frente a esta preocupación creciente, ofreciendo avances significativos en la mitigación de la contaminación del agua y un panorama esperanzador para el desarrollo sostenible de la industria textil. Su implementación adecuada y continuada puede conducir a prácticas más responsables y respetuosas con el medio ambiente para degradar y eliminar contaminantes utilizando microrganismos de manera efectiva.**

***Palabras claves*— Agua residual, Biorremediación, Biosorción, Contaminantes, Industria textil.**

I. INTRODUCTION

Industrial wastewater has become a global concern in recent decades due to its significant contribution of hard-to-remove substances in water treatment processes. The textile and food industries are among the first sources responsible for water pollution due to their numerous processes involving the generation of a significant proportion of these wastes, releasing a variety of pollutants [1], including fats, detergents, colorants, dyes, artificial sweeteners, synthetic substances and other chemicals, which do not adhere completely to fabrics or food, they are discharged as effluents and are harmful to both the environment and human health.

In the context of a global economy increasingly aware of the need to adopt environmentally friendly practices [2], the emoval of pollutants from wastewater has become an inescapable priority.

Based on a bibliographic review, wastewater of textile origin will be explored, considering its main components, the methods commonly used for its treatment and biosorption and bioremediation are proposed as sustainable alternatives to obtain more environmentally friendly discharges.

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Different databases were used using keywords such as wastewater, conventional methods, and filtering the search to the last, decade and which will present information of technical and scientific relevance.

II. CHARACTERIZATION OF WASTEWATER OF TEXTILE ORIGIN:

The wastewater generated by the textile industry presents a series of characteristics due to its dyeing, printing and finishing processes of textiles that require special attention.[3]Firstly, these waters usually contain a wide variety of chemical substances in their composition, such as colorants, dyes, surfactants, finishing products and bleaching agents and heavy metals, depending on the specific production processes used in the industry and the types of manufactured textile products.

Some of the main components present in textile wastewater are:

A. Dyes

They are one of the most prominent contaminants in textile wastewater. They can be of natural or synthetic origin, and their presence in water can cause environmental problems due to their chromatic intensity and potential toxicity. The textile industry uses and consumes different dyes, pigments and dyes, the estimated annual production of synthetic dyes is 700,000 tons [4]. According to estimates, up to 50% of the dyes used in the textile industry end up in discharged water due to their low degree of fixation in textiles [5].

Synthetic dyes are usually complex organic compounds that contain chemical groups such as azo, anthraquinone or phthalocyanine, among others. Since the synthesis of the first synthetic dyes, approximately 10,000 dyes have been produced, of which 30% are azo dyes, a group widely used in the textile industry, which represents around 70% of total production [3].

Azo dyes: Azo dyes are a class of synthetic dyes widely used in the textile industry due to their versatility and availability in a wide range of colors [6]. However, some azo dyes can be problematic, as they contain azo groups (N=N), which can be reduced to aromatic amines under anaerobic conditions. These aromatic amines can be toxic and carcinogenic to aquatic organisms and human health.

Reactive dyes: Reactive dyes, although they are highly efficient in fixing to textile fibers, form covalent bonds between the dye and the fiber due to the presence of their metal complexes [7], can also generate a significant contaminant load in wastewater. This is because during the

fixation process, only a portion of the dye adheres to the fibers, while excess dye and auxiliary chemicals are released into wastewater. These auxiliary chemicals, such as metal salts and cross-linking agents, can contribute to water pollution and sludge formation.

TABLE I
PRESENCE OF DYES IN TEXTILE WASTEWATER EFFLUENTS ACCORDING TO THEIR FIXATION [15]

Colorant Type	Fiber Class	Fixation degree	% in effluents
Acids	Polyamide	85-95	5-20
Basics	Acrylic	95-100	0-5
Azoics	Cellulose	70-95	5-30
Scattered	Polyester	90-100	0-10
Reagents	Cellulose	50-90	10-50

Disperse dyes: Disperse dyes, which are nonionic and used to dye synthetic fibers such as polyester, can present challenges in wastewater treatment due to their low water solubility. These dyes tend to be resistant to biological degradation [8] and can persist in wastewater even after.
Conventional treatment. Additionally, fine particles of dispersed dye can contribute to water turbidity and make it difficult for sunlight to penetrate receiving water bodies.

Basic dyes: Basic dyes are salt-based and cationic in form; Mainly used in acrylic fibers, they can be problematic in wastewater due to their cationic charge [9]. These dyes can interact with particles suspended in water and form insoluble complexes, which can contribute to turbidity and sludge buildup in treatment systems.

These compounds make the clarification and disinfection processes of wastewater difficult during its treatment due to the intense color they provide and their difficulty in degrading them using conventional methods. [3]The amount of dyes present in the water effluents depending on their fixation can be seen in table I.

B. Auxiliary chemicals

The textile industry uses a wide range of auxiliary chemicals in manufacturing processes, such as sizing agents, bleaches, dispersants, surfactants, leveling agents and dye fixing agents [10]. These chemicals may be present in wastewater in the form of unused substances or as byproducts of chemical reactions.
Sizing Agents: Sizing agents, also known as finishing agents, are used to improve the aesthetic and functional properties of

textiles, such as softness, wrinkle resistance and iron ability [11]. These agents contain polymeric compounds and surfactants [12], such as silicones and cationic compounds, which contribute to the contaminant load and negatively affect water quality.

Whiteners: Bleaches are used in the textile industry to remove stains and discolorations from textiles. Bleaches often contain hydrogen peroxide or compounds that release active oxygen during the bleaching process [13]. If not properly removed during rinsing, these bleaches are released into wastewater.

Dispersants: Dispersants are used to prevent the formation of precipitates and the deposition of impurities on textiles during dyeing and finishing processes. These chemicals help keep particles dispersed in the water, preventing their accumulation on textiles. However, some dispersants are not completely removed during washing processes [14] and rinse, remaining as contaminants in wastewater.

Fixing agents: Fixing agents are used to improve the fixation of dyes in textiles, ensuring greater color fastness [11]. These agents contain metal salts and reactive compounds, which directly affect water quality and aquatic ecosystems.

It is important to note that the impact of auxiliary chemicals on wastewater depends on several factors, such as the concentration used, the application method, treatment processes and proper effluent management.

C. Oils and fats

Lubricating oils and greases used in textile machinery and in spinning, weaving or finishing processes can be carried away by washing water and end up in wastewater. [4] These compounds can generate a layer on the surface of the water, making it difficult for oxygen to enter and negatively affecting aquatic life.

Finishing oils: Finishing oils, such as mineral oils and synthetic oils, are used in the textile industry to improve the properties of textiles, such as waterproofing. These oils make it difficult to remove suspended solids and reduce the efficiency of biological treatment processes.

Lubricating greases: Lubricating greases, such as petroleum-based greases or synthetic greases, are used in textile machinery to reduce friction and wear. During machinery maintenance and cleaning processes, these greases can be released into wastewater. These greases are difficult to remove by conventional wastewater treatment processes and tend to form oily films on the water surface, clogging treatment systems and affecting oxygen transfer in receiving water bodies.

Emulsifying oils: Emulsifying oils are used to form stable water-in-oil or oil-in-water emulsions. These emulsions are used in dyeing and finishing processes, as well as in the production of textile products, such as synthetic fibers. These oils can cause phase separation problems in wastewater treatment systems and make contaminant removal difficult.

Release oils: Mold release oils are used to facilitate the extraction of textiles from the molds during manufacturing processes. These oils may contain compounds such as paraffins, waxes and lubricants. If not removed properly, they form greasy films on the surface of the water.

D. Suspended solids

Suspended solids, such as textile fibers, dust or sediment, can be present in textile wastewater, contributing to the clogging of equipment and pipes, reducing system efficiency and increasing maintenance costs. These particles also reduce the transfer of oxygen from air to water, affecting biological treatment processes such as aerobic digestion and the activity of microorganisms responsible for degrading organic matter. [5] Additionally, they generate a decrease in the clarity of the water and an increase in its turbidity, which interferes in the filtration processes, separation of solids, and leads to an increase in sedimentation, favoring the formation of sludge in the different stages of wastewater treatment. the self-purification capacity of the receiving bodies.

E. Heavy metals

In the production process of the textile industry, some dyes and chemicals contain heavy metals, which have a significant impact, making conventional wastewater treatment difficult and can be toxic even at low concentrations [4]. Among the most common heavy metals in the textile industry, copper (Cu) stands out, which causes an increase in turbidity, alters the color and modifies the pH of wastewater, lead (Pb) which interferes with coagulation processes. and flocculation, making the formation of flocs and the separation of particles difficult, cadmium (Cd) that accumulates in the tissues of aquatic organisms and interferes with the precipitation and adsorption processes, Mercury (Hg) which is extremely toxic, bio accumulative, and adsorption on activated carbon or chemical precipitation, for efficient removal. And finally, chromium (Cr), which can exist in its trivalent (Cr (III)) or hexavalent (Cr (VI)) form, which is a toxic and carcinogenic agent, [15] whose presence in textile wastewater can cause serious problems. environmental, and require special treatments such as chemical reduction or specific adsorption for effective removal.

F. Organic and inorganic compounds

In addition to dyes and auxiliary chemicals, textile wastewater can contain a variety of organic and inorganic compounds such as polycyclic aromatic hydrocarbons (PAHs), amines, formaldehyde, volatile organic compounds (VOCs) that tend to evaporate easily and generate unpleasant odors in wastewater and other chemicals with high concentrations of nutrients such as nitrogen and phosphorus, due to the use of fertilizer chemicals in the stamping and finishing processes. These nutrients promote excessive growth of algae and aquatic plants in receiving water bodies, causing eutrophication problems.

These predominant polluting substances in the production process of the textile industry are usually toxic and persistent in the environment, degrading the aesthetic quality of the receiving bodies [16], increasing biochemical properties, affecting aquatic ecosystems, the metabolism of fauna, the development of photosynthesis, preventing the growth of flora, promoting resistance, bioaccumulation, toxicity and representing a risk to human health due to the increase in carcinogenic and mutagenicity factors [17].

Another relevant characteristic of industrial wastewater is its high organic load, due to the presence of persistent compounds that consume dissolved oxygen, generating the death of many organisms present in water sources.

In addition to chemical contaminants, these effluents can contain high levels of suspended solids, unbalanced pH, high chemical demand (COD) and biochemical demand (BOD) for oxygen, decreasing their biodegradability [18].

Given the complexity and diversity of its contaminants, wastewater of industrial origin, especially from the textile and food industry, requires exhaustive characterization before treatment and discharge, through physicochemical and biological analyzes that determine the concentration and toxicity of the different contaminants. contaminants present.

The characterization of industrial wastewater allows us to evaluate the environmental impact of the textile industry and are fundamental indicators for the design, construction and efficient operation of treatment plants, because they allow us to select the most appropriate technologies and establish the control parameters that guarantee efficient removal of contaminants.

Some key parameters to consider are the following:

A. pH

pH is a measure of the acidity or alkalinity of wastewater wastewater, it is an important parameter, it can vary depending on the processes and chemicals used [2]. Extreme pH values negatively affect aquatic organisms and treatment systems, reducing the efficiency of the coagulation, flocculation and precipitation processes used.

B. Biochemical oxygen demand (BOD)

BOD is a measure of the amount of oxygen that microorganisms need to biodegrade organic substances present in wastewater. BOD is used to evaluate biodegradable organic load and biological treatment capacity. A high BOD value indicates a higher biodegradable organic load, which may require more efficient biological processes.

C. Chemical oxygen demand (COD)

COD is a measure of the amount of organic substances and some inorganic substances present in wastewater that can be chemically oxidized. This parameter indicates the total organic load and oxygen consumption capacity of the wastewater. A high COD value indicates a higher organic load and may require more intensive biological or chemical treatment steps.

D. Total suspended solids (TSS)

TSS represents the amount of solid particles that are suspended in the wastewater. These particles can include organic matter, inorganic particles, textile fibers and other contaminants. TSS are an indicator of wastewater turbidity and clarity, and their removal is typically performed in pretreatment stages such as sedimentation or filtration.

III. CONVENTIONAL WASTEWATER TREATMENT METHODS

A. Adsorption

Adsorption is one of the most effective textile wastewater treatments, because the matter and dyes are transferred to a surface of highly porous solid particles [19], activated carbon is one of the most used adsorbents [20]. However, this technique requires pretreatment of the samples to avoid clogging of the filters by the suspended solids contained therein.

B. Cation exchange

It is a process by which cationic contaminants, such as dyes, heavy metals and salts, are eliminated [21], this technique uses strong cationic resins with positively charged functional groups, such as sulfonic groups (-SO3H) or phosphonic groups (-PO3H2) or weak cationic resins with carboxylic groups (-COOH) or amino groups (-NH2) and takes advantage of the properties of attraction between charged ions to generate that the undesirable cations of the wastewater and the contaminants are exchanged for sodium or hydrogen ions of the resin, leaving other functional groups attached and allowing the collection of the treated water at the end of the column[22]. As the resin becomes saturated with cationic contaminants, its exchange capacity is exhausted, requiring a regeneration process to continue its operation in the treatment process. This process has the limitation that it does not work for anionic compounds such as detergents.

C. Biological treatment

Wastewater treatment with activated sludge is a widely used biological process to remove contaminants and occurs in 2 main stages: Aerobic Stage: In the aerobic stage, wastewater is mixed with activated sludge, which is a diverse population of microorganisms. Aerobics [11]such as bacteria of the genus *Pseudomonas* that degrade hydrocarbons, phenols and synthetic chemicals; *Aeromonas* efficient in the elimination of nitrogenous compounds [23], such as ammonium and nitrate, *Bacillus* effective in removing fats and oils [24], *Acinetobacter* capable of decomposing recalcitrant organic compounds, among others, protozoa of the genera *Paramecium, Tetrahymena* and *Vorticella* that use their cilia to capture and engulf bacteria, allowing the biological balance of the system to be controlled [25], maintaining the appropriate, diverse and healthy microbial community, favoring the removal of organic matter and improving the efficiency of the treatment. Finally, some fungal mycelia of the genus *Trichoderma* stand out that produce ligninolytic enzymes and cellulases that help degrade dyes and *Aspergillus* capable of degrading recalcitrant organic compounds and can help in the elimination of textile dyes and phenolic compounds.

During this aerobic stage it is important to guarantee adequate temperature, pH, agitation and dissolved oxygen conditions to ensure a uniform distribution of the interaction between microorganisms and contaminants.

Once the aerobic stage is completed, the wastewater passes to the Sedimentation Stage: In this stage, the activated sludge and biological contaminants form heavier flocs that settle at the bottom of the sedimentation tank, the clarified water is removed at the top. top of the tank and undergo a final disinfection stage before being released into the environment.

D. Chemical oxidation

Chemical oxidation processes use oxidizing agents such as ozone that are capable of selectively oxidizing unsaturations [26] and aromatic structures[9], is an effective technique in bleaching acid dyes [27], but it only has a slight effect in terms of reducing total organic carbon [28] or hydrogen peroxide by the Fenton reaction [29], to break down organic compounds and remove contaminants from textile wastewater [30]. Photochemical oxidation processes are also used that combine UV radiation with compounds such as titanium oxide [31], where UV radiation activates these catalyst compounds, providing the appropriate conditions to oxidize the dyes efficiently and without producing odors, sediments or electrolytic oxidation that allows the hydrolysis of dyes by controlled potentials or by reagents produced by electrolysis,[15,32] generating the conversion of organic matter to less polluting compounds using electric current [33,34].

Conventional wastewater treatment processes are often ineffective in completely eliminating these pollutants, which has prompted the search for new treatment alternatives, which allow wastewater containing dyes to be effectively managed using eco-technological methods to avoid adverse effects on the environment. environment, human health and natural water resources.

E. Inverse osmosis

Reverse osmosis is a technique used to remove hydrolyzed reactive dyes [35], auxiliary chemicals producing a high quality of permeate, and allowing the recovery of treated water.

IV. Alternative wastewater treatment methods

Bioremediation and biosorption have emerged as promising technologies for the treatment of industrial wastewater, providing sustainable and efficient solutions to the problem of aquatic pollution.

A. Bioremediation

Bioremediation is a natural process that takes advantage of the capacity of certain microorganisms, such as bacteria, fungi and algae [36], to degrade and transform toxic substances into less harmful compounds or even into harmless products [37]. This process can occur in natural systems, such as wetlands and treatment ponds; or controlled systems such as wastewater treatment plants [38, 39]. In the case of textile wastewater, bioremediation can be applied in several ways:

1. Aerobic bioremediation

It is one of the most used techniques, where microorganisms are introduced into the wastewater and oxygen is provided that promotes the degradation of contaminants [40]. These aerobic microorganisms use the organic compounds present in wastewater as sources of carbon and energy, transforming them into carbon dioxide, water and biomass [35,26]. This technique effectively removes compounds such as dyes, surfactants and other organic contaminants.

2. Anaerobic bioremediation

It is a technique that is carried out in the absence of oxygen. In this process, aerobic microorganisms break down organic pollutants into simpler compounds, such as methane and carbon dioxide [41]. It is a particularly efficient technique in removing recalcitrant and toxic compounds such as dyes and persistent chemicals.

B. Phytoremediation

It is another bioremediation technique that uses plants to remove contaminants present in wastewater [42]. Some plants have the ability to accumulate heavy metals and other toxic compounds in their tissues [43], allowing its extraction and decontamination from the water [44]. In addition, plants also release organic compounds into the soil that tend to promote microbial activity and favor the degradation of contaminants.

C. Biofiltration

It is a technique that uses a layer of microorganisms attached to a filter medium, such as sand, activated carbon or peat, to degrade the organic compounds in the dyes [45] and chemical substances: The wastewater passes through the filter medium and the microorganisms present in it decompose the compounds, eliminating them from the water [46]. Biofilters can be used as a treatment stage in treatment plants or in specific filtration systems.

D. Enzymatic Bioremediation

Some enzymes produced by microorganisms have the ability to accelerate the chemical reactions necessary to break down dyes and chemicals [47]. These enzymes, such as *laccases*, which allow the degradation of aromatic structures, generate free radicals and peroxides that oxidize the chromophore groups present in the dyes and break the chemical bonds, facilitating the elimination of phenolic compounds and azo dyes; *peroxidases* that use hydrogen peroxide as a co-substrate [48], allowing the oxidation and discoloration of the chromophore groups, modifying its chemical structure and decreasing the intensity of the color [49], act mainly on phenols and aromatic amines. *Ligninases* that degrade lignocellulosic compounds, breaking the chemical bonds present in the dyes [49], breaking them into smaller fragments, *proteases* that catalyze the degradation of proteins present in textile waste; these enzymes help break down the peptide bonds in proteins, turning them into smaller peptides and amino acids [50], facilitating the elimination of protein residues and reducing the organic load in waste water, *lipases* that decompose the lipids and fats present in textile waste, hydrolyzing the ester bonds of lipids, releasing fatty acids and glycerol. By breaking down lipids, *lipases* help eliminate fatty components present in wastewater and reduce the formation of unwanted foams.

E. Membrane bioreactors

Membrane bioreactors (BRM) are systems that combine bioreactor technology with membrane filtration for the treatment of textile wastewater. These systems combine the biodegradation of contaminants by microorganisms with the physical separation of solids and biomass through semipermeable membranes, offering high quality of the treated effluent [51], increased space efficiency due to combined biological and separation processes, and increased resistance to charge fluctuations and toxicity shocks.

There are several types of membrane bioreactors used to treat textile wastewater. Some of the most common are activated sludge membrane bioreactor (MBR), which uses the activated sludge process for microorganisms in the activated sludge to biodegrade organic contaminants in wastewater combined with submerged or ultrafiltration membranes [17], which will retain suspended solids and microorganisms, allowing the treated water to pass through them; membrane biofilm bioreactor (MBBR), in this type of bioreactor, a biofilm is formed on a support or growth medium suspended in the reaction tank that provides a surface for the growth of microorganisms [52,53] that break down pollutants. MBBRs effectively remove organic contaminants and nutrients such as nitrogen and phosphorus present in textile wastewater. Anaerobic Membrane

F. Bioreactor (AnMBR)

This bioreactor combines membrane technology with anaerobic processes, where microorganisms decompose organic contaminants in the absence of oxygen, effectively reducing chemical oxygen demand (COD) and biogas from organic contaminants present in the textile wastewater.

However, this technique requires higher investment and maintenance costs due to the presence of membranes and the need for regular cleaning and replacement.

G. Biosorption

The Biosorption technique consists of the passive adsorption of toxic substances by living, dead or inactive biological materials, such as microorganisms, bacteria of the *Pseudomonas* type, *Bacillus*, *Escherichia coli* and *Shewanella*, known for their ability to adsorb and reduce heavy metals, Algae such as *Chlorella*. and *Scenedesmus*, *cyanobacteria*, such as *Spirulina* and *Microcystis* that adsorb and accumulate heavy metals [54], nitrogen and phosphorus, fungi such as *Aspergillus*, *Trichoderma* and *Penicillium* efficient in the adsorption of heavy metals due to their high chitin content, which facilitates binding with metal ions, yeasts such as *Saccharomyces cerevisiae* and *Candida utilis* whose cell surface is rich in functional groups , allow it to interact with contaminants and adsorb them biological byproducts, enzymes and lignocellulosic materials, which have the ability to act as adsorbents for certain types of contaminants present in wastewater [55], accumulating them inside through chemical and biological interactions. It allows you to remove dyes, heavy metals, organic compounds and other organic and inorganic contaminants [56].This technique can occur by physical adsorption, where the contaminants physically adhere to the surface of the biomass due to electrostatic, van der Waals or hydrogen forces, in a rapid and reversible process, by chemical adsorption, thanks to the binding of the contaminants with the hydroxyl, carboxyl, amino or sulfhydryl functional groups, present in the biomass in a way that is stronger and less reversible than physical adsorption or bioaccumulation, where the tissues or cells of living organisms absorb contaminants and these accumulate in their inside. This process is especially relevant in the accumulation of heavy metals by certain species of microorganisms.[57].

The biosorption process in the treatment of textile wastewater has the advantage of affecting a selective removal of specific contaminants and biological organisms can be modified or treated to increase their adsorption capacity, and even allows the use of biomaterials derived from the agricultural industry or forestry. However, it refers to optimal environmental conditions for the growth and activity of organisms, the possible inhibition or toxicity of certain contaminants on organisms, and the need to regenerate or deactivate the biomass used after the biosorption process.

Annex I summarizes the various methods of textile wastewater treatment, taking into account some of their advantages and limitations.

V. Benefits and challenges

Conventional biological treatment is very commonly used for the biodegradation of compounds due to the advantages that the process is relatively economical, has low operating costs and can produce a clean effluent after partial or total degradation of the initial product, although they can be slow (between 12-24 hours) and generate sludge. On the other hand, the use of fungi manages to remove a high percentage of dyes in sterile conditions and with operation times between 12 and 24 hours, guaranteeing a process without the generation of byproduct [25]. Enzymatic treatment, for its part, is a process with short residence times of approximately 1 due to the high degradation kinetics, acting for the conversion of substances.

Bioremediation of textile wastewater has numerous benefits. Firstly, they are more sustainable alternatives compared to conventional wastewater treatment methods, such as chemical oxidation or adsorption on activated carbon [59], which can be costly and generate undesirable byproducts.

The use of enzymes in the degradation of dyes has several advantages. Primarily, enzymes have a great capacity to accelerate chemical reactions and are highly specific in their action, which means that they can selectively target certain compounds without affecting other components present in the wastewater [58], minimizing the generation of unwanted byproducts and reducing toxicity.

Additionally, they can operate in mild conditions, such as moderate temperatures and neutral pH ranges, consuming less energy and reducing environmental impact compared to other degradation methods that require extreme conditions.

However, there are also challenges associated with the use of enzymes, because some can be expensive to produce on a large scale, limiting their application in the textile industry. Furthermore, they are usually sensitive to adverse conditions such as very high concentrations of contaminants, heavy metals or chemical inhibitors present in wastewater, which is why it is necessary to carry out research to optimize their production, stability and efficiency in industrial applications.

VI. Conclusion

Dyes are natural and synthetic compounds that enhance the beauty of the world with colored products, however, they are pollutants of some water sources. The textile industry will continue to be an important focus of attention regarding efforts to conserve water and the search for more sustainable and green methods that eliminate as much pollution as possible from final effluents.

The treatment of these industrial wastewaters is a problem that has not been satisfactorily resolved by existing physicochemical and biological methods. This review compares various methods and outlines some of the advantages and disadvantages of each method's role in bleaching contaminated tributaries.

Firstly, physical methods only transfer contaminant molecules to another phase instead of destroying them and are efficient for small volumes, then the main drawback of chemical processes is the need for a pretreatment process, their high cost for the acquisition of chemical products and the disposal of the sludge generated. And finally, it is evident that alternative methods have greater ranges of operability in terms of pH, temperature, salinity conditions and allow us to observe their potential regarding the use of clean technologies, biological materials, such as algae, fungi and bacteria, to adsorb and accumulate contaminants into your cells without producing byproducts or secondary contaminants.

These processes have proven to be effective in removing a wide range of contaminants, including dyes, and present significant advantages over conventional methods in terms of cost, efficiency and sustainability.

ANNEX I
CURRENT AND EMERGING DYE REMOVAL TREATMENTS IN TEXTILE EFFLUENTS [58]

Method	Advantage	Limitation
	Physicists	
Precipitation, coagulation, flocculation.	Short time and low cost	Solids separation
Adsorption	They generate high quality effluents	Slow and non-selective processes
Activated carbon	Broad dye removal	High implementation cost
Filtration membranes	Removal of all types of dyes	Production of concentrated sludge
Ion exchange	Regeneration without loss of absorbent	Not effective for all dyes
	Chemicals	
Fenton process	Eliminates soluble and insoluble dyes, high discoloration speeds	Generates sludge, high cost of reagents
Ozonation	Effective in gaseous state, does not generate waste or sludge.	Pot life 20 min, not suitable for disperse dyes
Photochemical Oxidation	Effective, Does not generate sludge or odors	It requires a radiation source, a slow process, forms byproducts and is ineffective at an industrial level.
Electrochemical oxidation	Degrades a large amount of toxic compounds, does not require the addition of chemicals	High energy consumption generates byproducts through parallel reactions
Electrokinetics	Economically feasible	High sludge production
	Biological	
Aerobic Bioremediation	Partial or total discoloration for all types of dyes	High cost treatment
Anaerobic Bioremediation	Resistant to a wide variety of complex dyes	Long acclimatization phases
Enzymatic bioremediation	Effective for specifically selected compounds	Requires isolation and purification

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