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Potential environmental and health risks of textile dyes and mechanisms treatment for Environmental safety by algae-based technologies: A review

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Abstract:

Dyes used in the textile industry pollute many bodies of water, and the continuous release of this colored water into aquatic environments without treatment is one of the major challenges in the world. Textile dyes reduce water quality and visual appeal, increase biochemical oxygen demand (BOD) and chemical oxygen demand (COD), inhibit photosynthesis, enter the food chain, accumulate in organisms, promote toxicity and mutagenicity, and cause cancer. Conventional methods are ineffective in removing these pollutants. Therefore, searching for new, environmentally friendly, effective, low-cost, and sustainable technologies to remove these pollutants has become necessary. One of these methods is the biological method based on algae. Microalgae has unique properties that make it a promising solution for removing industrial dye pollutants, such as rapid growth and high density; it tolerates difficult growth conditions and converts pollutants and nutrients into high-value and economical compounds. This review provides a comprehensive overview of dyes used in the textile industry, their environmental and health impacts, and physical, chemical, and biological dye removal mechanisms with pros and cons, emphasizing the algae-based biological method of dye removal from industrial wastewater.

Keywords: Textile dye, Aquatic environment, Biological method, Phycoremediation, Algal-based technologies, Textile wastewater.

Introduction

Textile dyes are among the most dangerous water contaminants in the world, and they are the second-biggest polluter globally. In most developing countries, textile manufacturers dump liquid waste into the environment. Contaminated water from the textile industry may contain a variety of hazardous and toxic substances that pose a risk to human health and aquatic life [1]. It has been detected in aquatic environments at levels up to 1 mg/ [2]. And there are a number of major industries responsible for releasing dye compounds into the aquatic environment, namely the textile sector (54% in the first place) , the dyeing industry 21% the paper , pulp industry (10%), the tanning (8%), and the production of dyes 7%, figure 1 [3]. The textile industry generates significant wastewater containing persistent contaminants, including synthetic dyes and metals, the yearly production of synthetic dyes is estimated at 7 x 10^7 tons, of which over 10,000 tons are utilized in the textile sector[4]. This industry, which is the backbone of the global economy, is, regrettably, also the primary cause of environmental pollution in several nations, including Malaysia, India, Pakistan, Bangladesh, and China, during the textile production stages, textile industries consume much potable water [5]. The wastewater from the textile contains hazardous pollutants like amines, phenolic compounds, acids, alkalis, hydrocarbons, salts, and heavy metals, which have detrimental environmental and public health impacts [6,7] .After the textile dyeing process, Concentrated dye wastewater from textile dyeing is often discharged into aquatic environments at extreme temperatures and pH levels without treatment, interfering with O_2 transport and natural water systems' ability to purify[8,9] . Even though dyes make up less than or equal to 1 ppm of industrial effluent, their complex structure makes them extremely stable and resistant to light, chemical reactions, and biological activity, allowing them to last longer in the environment. Their buildup raises the need for demand for biochemical oxygen demand (BOD) and chemical oxygen demand (COD), affecting pH [10]. Their presence causes turbidity in the water, prevents the growth of algae and aquatic plants, and is a cause of cancer and mutants. Their presence causes turbidity in the water, prevents the growth of algae and aquatic plants, and is a cause of cancer and mutants [11; 12]. Skin inflammation, mucous membrane irritation, respiratory problems, and may be toxic to aquatic organisms due to containing heavy metals, chlorine, and another toxic material [13,14]. Dyes can be categorized into broad groups, Based on their sources, dyes can be categorized into natural or synthetic groups, and based on their general structures, and they can be categorized into anionic, non-ionic, and cationic groups. Furthermore, based on the application characteristics, dyes can be classified into various groups including acidic, basic, reactive, mordant, sulfur dye, direct, pigment, vat, azo insoluble, and dispersion , figure 2 [15] .

Numerous physical and chemical techniques have been employed by researchers to eliminate contaminants like dyes from wastewater [16]. The technologies employed in water treatment encompass membrane filtration, electrochemical treatment, ion exchange, sedimentation, osmosis, and evaporation. However, the majority of these technologies are neither environmentally benign nor economically viable [17]. The primary challenges associated with these systems are their exorbitant cost, restricted water extraction capabilities, demanding maintenance needs, and the generation of perilous byproducts. Consequently, there is an imperative need to explore the most appropriate approach for effectively analyzing or eliminating colors from wastewater [18]. Biological treatments rely on the metabolic activities of living organisms to break down and convert wastewater pollutants into biomass and gases (CO_2, CH_4, N_2, and SO_2), reduce BOD and COD levels, and improve effluent quality [19].Biological treatments use a variety of microorganisms, such as bacteria, fungi, yeast, and microalgae, to degrade various pollutants [20]. Many studies indicate that algae-based bioremediation to remove dye from

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wastewater is a promising and environmentally friendly alternative when compared to other traditional techniques [21,22,23,24].

Microalgae wastewater treatment has recently received increased attention due to its adaptability to different wastewaters, low energy requirements, ability to grow in difficult circumstances, rapid growth and high density, and ability to transform nutrients into high-quality products. These properties could make the use of microalgae for industrial wastewater bioremediation extremely promising[25,26,27]. Through a variety of processes, including biosorption, bioaccumulation, and biodegradation, microalgae eliminate a wide range of pollutants, including dyes , for example, the species of algae Ulva sp., Spirulina sp., Sargassum sp., Scenedesmus sp., Phormidium sp., and Spirogyra sp. can remove dyes via accumulation and biosorption mechanisms [28]. Certain algae can metabolize dyes through enzymatic biodegradation processes, which leads to the breakdown and detoxification of dyes. For instance, it has been demonstrated that *Chlorella vulgaris* can effectively remove colors from effluent by biodegradation, including Congo Red, Remazol Brilliant Blue R, and Brilliant Blue R [29,30].The present review focuses on the detrimental effects that dye-contaminated water has on aquatic ecosystems and human health, as well as the advantages and disadvantages of the various mechanisms used to remove these pollutants. It also emphasizes the significance of using algae-based treatment systems to treat industrial liquid waste, as these systems offer a viable and sustainable approach to treating liquid waste in the industry.

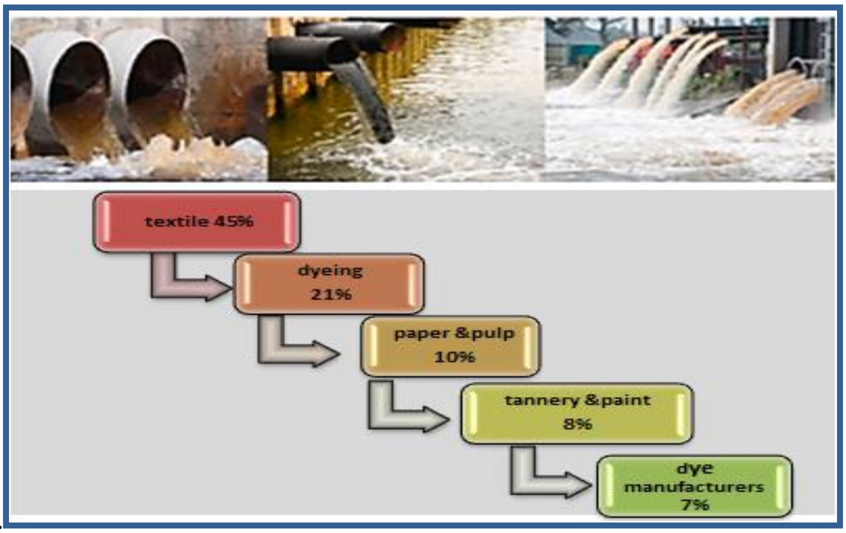

Fig1: industries responsible for dye discharges into the aquatic environment

Synthetic dye utilized in the textile sector

Dyes are chemical substances that have the ability to absorb light in the visible spectrum, namely in the wavelength range of 400 to 700 nanometers. Dyes can be classified into various groups according to the chromophoric groups based on their molecular structures (as anthraquinone, azo, phthalocyanine, etc.); Industrial application (reactive cotton, polyester, etc.); how they dissociate into a fluid solution (acidic, basic (cationic), direct reactive (anionic), and disperse(nonionic); and also, its level of toxicity can be classified into environmentally friendly, low-toxic, and high-toxic [31]. Figure 2 shows the types of industrial dyes used in textile industries.

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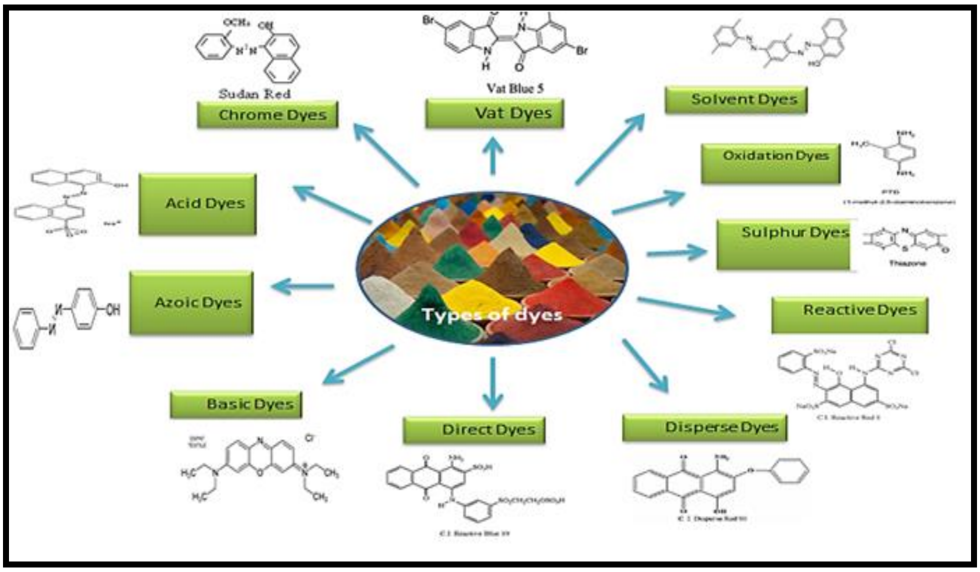

Fig.2 the types Synthetic dye used in textile industries

In the textile industry, natural dyes are mainly derived from microbes, plants, animals, and minerals such as safflower (*Carthamus tinctorius*), henna (*Lawsonia inermis L.*), and turmeric (*Curcuma longa*),they are less toxic, easier to decompose by microbes, and environmentally friendly [28].On the other hand, there are some limitations, like poor fastness, low textile substrate affinity, difficulty reproducing shades, and high cost [32], but they have a weak bond with textile fibers , so they have been replaced by industrial dyes resulting from organic or inorganic compounds, synthetic dyes offer a wide range of colors, consistency, affordability, availability, and durability; they can withstand harsh conditions; they have a vast production capacity, making them more accessible and versatile; and their chemical properties also make them suitable for various materials and applications compared to natural dyes include direct, acidic, reactive, basic, sulfur, dispersed, and other dyes that are included in these categories , table 1 [33]. But on the other hand, they include hazardous and poisonous substances such as lead, toluene, chromium, copper, mercury, and benzene, which can cause cancer, allergies, and skin irritation. Furthermore, they are not biodegradable, so they have long-term negative effects on the environment [34].

Table 1. Properties and applications of type synthetic dyes used in textile industries

Type dyes	Examples of dyes	Applications of textile dyes	Application pH	Reference
Direct dye	Direct dye 81, Direct dye 75 Direct Yellow 12, Direct Black38 ,Direct Orange 38,Direct Brown 95	cotton, wool, leather leather and nylon	7	[31,35]
Acid dyes	Acid Blue 78 ,Congo red, Acid Blue 45, Acid Blue 158Acid Black1 , Acid Blue 25	flax, leather, wool, silk, and cotton, modified acrylic fibers	4-5	[2]
Basic dye	Basic brown, Basic red, and Methylene blue Brilliant green, Aniline yellow, Crystal violet10, and Basic blue	Modacrylic nylon, wool, silk, and polyester	6-7	[35,36]
Sulfur dyes	Sulfur Red 7, Sulfur Brilliant Greenand ,sulfur black 1,Sulfur Yellow GC.	Cellulosic, fibers	10-11	[36,37]
Disperse dye	Disperse red 45,Disperse red 60, Disperse Blue 27, and Disperse yellow26	Polyamide, polyester fibers, Nylon polyacrylonitriles	4-5	[36]
Dye Vat	Vat Brown 45, Vat Blue 36, Vat Violet 18 and Vat Black 27	Rayon fibers, wool, flax, and wool	12-13	[2]
Dyes Azoic	Triazo, diazo, and monoazo dyes	paper paint, leather, and Nylon	-	[31]

Removal of Textile Dyes from Wastewater

The lack of clean drinking water is a global problem, with 47% of the world's population expected to face it by 2030 [14]. In middle- and low-income countries, clean water is an expensive resource [38]. 700,000 tons of dyes are produced every year, with over 100,000 of them already on the market, out of this total, about 15% is released into the environment after usage and is notoriously difficult to break down [39] . Textile industries consume large quantities of purified water, and textile dyes contain chromophores, which are toxic hazardous substances that may be toxic, mutagenic, and carcinogenic [40,41]. Therefore, it is imperative to find sustainable methods for eliminating dyes from wastewater before their release into the aquatic ecosystem, dyes can undergo treatment through three methods: chemical, physical, and biological[42]. Figure 3 displays the primary technologies used for wastewater treatment

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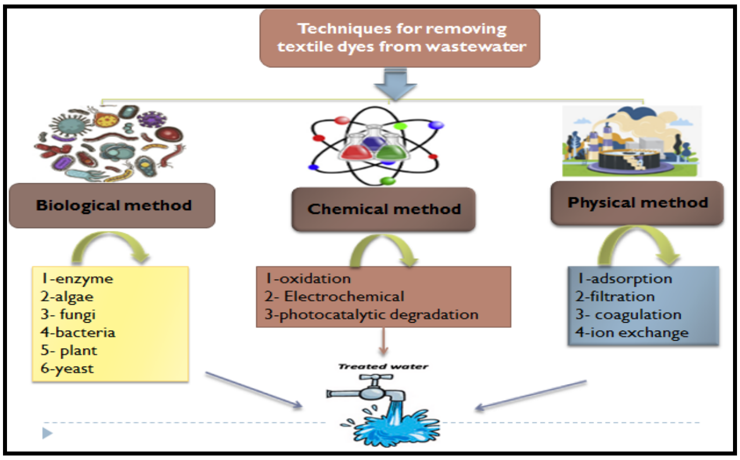

Fig. 3 : Techniques for removing textile dyes from wastewater

Physical method of Removing Textile Dyes

The adsorption method is one of the most important physical techniques and is the most effective, important, and useful for removing pollutants from wastewater, there has been a noticeable increase in interest in these systems, and their working principle is the surface phenomenon that, they attract atoms or molecules, ions on the surface of solid objects lead to the removal of many contaminants such as dyes [43,44].Membrane filtration technology has also been widely used in industrial and domestic environments, there are different types of membranes classified based on pore size, such as microfiltration, nanofiltration. superoxide, and membranes reverse osmosis[45, 46]. Ion exchange technology has recently received great attention in the treatment of wastewater and liquid waste from textiles due to its high efficiency, simplicity, modernity, and versatility ,the strong bond between the solutes and the resins used in the reactor allows for the good separation of ions exchange process [47]. Physical method advantages are ease of operation, simplicity of design, lack of toxins, low operational impact, and low chemical requirements. However, certain drawbacks accompany this approach, including exorbitant operational expenses, restricted applicability, and the generation of substantial amounts of hazardous sludge, posing challenges to its proper disposal [48,49]. Figure 3 explains the advantages and disadvantages of some significant strategies used in physical processors.

Chemical Methods of Removing Textile Dyes

The chemical process is regarded as a significant approach for eliminating textile colors from wastewater to improve the quality and purity of water, It is executed using a chemical procedure, which is one of the swiftest and most effective techniques. The predominant chemical methods employed in wastewater treatment include advanced oxidation processes, electrochemical breakdown, photocatalysis, coagulation, and flocculation, figure 3 [56] .However, these methods have several disadvantages, including the need for specialized equipment, the substantial electrical power demands of the reactors, the significant utilization of reagents and chemicals, and the accumulation of concentrated materials. The excessive use of chemicals in sludge leads to secondary pollution, resulting in increased costs [57]. presents an overview of the advantages and disadvantages associated with various chemical techniques used to eliminate dye from water table 2 .

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Table 2: Advantages and disadvantages of different chemical, biological, and physical techniques for removing synthetic dyes.

Physical processors	advantages	disadvantages	reference
Adsorption	This method removes a variety of dyes, renewable and economical sorbents, and good efficiency	Adsorbents must be removed after use, have low adsorption surface area , and are quite costly	[9,50]
Ion exchange	It is possible to reuse it. High efficiency in removing dyes produces high quality water.	It requires constant maintenance, is expensive, and removes a limited number of dyes	[51]
Membrane fltration	efficient in recovering and reusing water	There is a significant upfront cost, membrane fouling happens, and concentrated sludge is produced.	[43,50]
Reverse osmosis	It can remove a number of dye colors and produce water of high purity and quality.	high running costs, significant maintenance, and high-pressure requirements	[50]
Chemical methods			
Advanced oxidation approaches	High-efficiency removal of both soluble and insoluble dyes, requires no energy input.	they are costly, sensitive to pH, and generate hazardous byproducts and sludge production.	[52]
Electrochemical	Moderate metal selectivity, no formation of sludge, does not need additional chemical material	High costs effective and less active from other method, Reduced dye removal is the result of high flow rates and high electrical use.	[53,54].
Coagulation flocculation	Cost-effective, and essential method in textile wastewater treatment.	greater PH sensitivity, expensive chemical requirements and no recycling.	[50,55]

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Biological methods of removing textile dyes

Biodegradation and bioremediation occur naturally in wastewater and contaminated settings due to the presence of suitable microbes like bacteria, fungi, yeast, and algae. Biodegradation technology, which can be induced in labs and scaled up for textile effluent treatment and decolorization, uses microorganisms to transform toxic wastewater particles into harmless or helpful compounds [58, 42]. Biological methods for purifying water tainted with dyes have garnered significant interest in recent times owing to their exceptional efficacy, economic viability, ecological compatibility, and broad applicability to various dye categories. Wastewater treatment encompasses several mechanisms, such as mineralization, dilution, bioaccumulation, adsorption, and biosorption. [59, 60]. Biological treatments of textile dye waste are more practical and sustainable than physical and chemical methods due to their ease of use, affordability, energy-saving features, absence of toxicity in byproducts, and environmental safety [38]. The most important of these processes is adsorption and decomposition to remove the dye color [61].

Removing textile dyes using algae-based techniques

Algae, a diverse group of organisms, serve as the primary producers in aquatic ecosystems. They utilize photosynthesis to convert carbon dioxide into organic matter, thereby supplying nutrition and energy to other aquatic organisms. Experts estimate that up to 70% of Earth's oxygen comes from algae and other marine plants [62].Algae species have evolved diverse methods for detoxifying and purifying contaminated water, such as in situ and ex-situ biodegradation, bioaccumulation, biotransformation, biomineralization, and biosorption, enabling them to grow and thrive in water contaminated with various types of organic pollutants [63]. Microalgae can aid in the removal of color from textile dyes through three biological processes: biosorption, bioaccumulation, and biodegradation. These mechanisms are interrelated and influence each other [64].

Biosorption is the process by which pollutants are passively attached to the surfaces of living or dead biomass. This can happen through physisorption, chemisorption, Van der Waals forces, or electrostatic forces [65]. Algae possess a significant capacity for biosorption and are readily accessible, rendering them a highly promising resource for biosorbents. Consequently, there is a growing inclination towards utilizing algae as possible agents for adsorption in the treatment of wastewater, figure 4 , the reason for this is the existence of sulfated polysaccharides within the cellular structures of macroalgae, particularly in the fibrous matrix and intercellular vacuoles, and hydroxyl, sulfate, and carboxyl groups found in its walls are regarded as potent ion exchangers [40].

The biodegradation process involves breaking down complex compounds into simpler molecules through enzymes like azoreductase, laccase peroxidase, and polyphenol oxidase. These enzymes work by metabolizing the dye and breaking the bonds in the chromophore groups, thus getting rid of the dye residue from the middle [66]. The most common way to break down dye in aquatic environments is through the enzyme azoreductase, which splits the azo bonds in the dye, forming aromatic amines, algae catabolize these aromatic amines into carbon dioxide and water with the help of reductase enzymes. The algae thus convert the complex dye molecules into simpler, harmless substances, and this process, called mineralization, helps reduce the negative effects of pollutants (dyes) on the environment[28,46] .

Bioaccumulation, as opposed to biosorption, is an active metabolic process that uses a variety of cell substrates, and it is slower and more energy-intensive, despite their differences, bioaccumulation and biosorption are dynamically mutual processes, making it difficult to estimate the amount of contaminants absorbed and bioaccumulated, figure 4 [44].

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Several studies have reported the ability of algae to remove dyes using these two processes. For instance, it has been demonstrated that *Chlorella vulgaris* can effectively eliminate dyes from wastewater, including Congo Red, Remazole Brilliant Blue R, and Brilliant Blue R [67]. In a similar study, Gelebo *et al*. [49] noted the capacity of the algae Oscillatoria sp. to remove the malachite green dye, methylene blue, and safranin; the removal rate was 93%, 66%, and 52%, respectively. In another study, Abou-El-Souod et al. [50] reported on the removal of the dyes methyl red and Congo red at 55.45% and 62.05%, respectively, by the algae *Scenedesmus oblique*. In a study conducted by Goda *et al*. [68], it was discovered that the green algae *Chlorella vulgaris* can break down Congo red dye in both water and wastewater at a rate of 89.6% within 13 days through the process of biodegradation

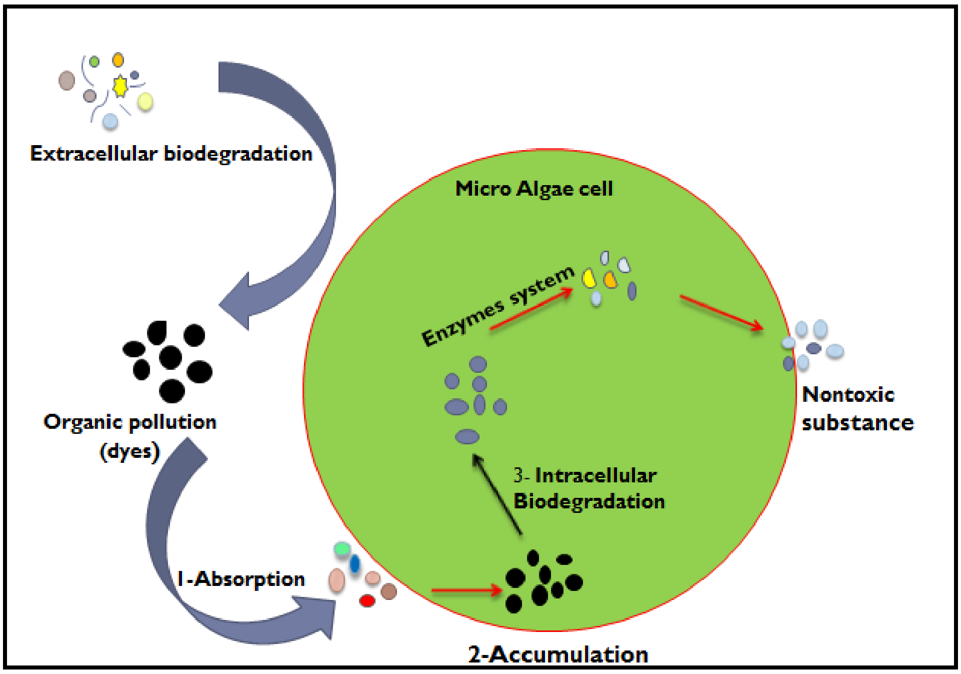

Figure 4: Mechanisms of bioremediation of textile dyes through microalgae

Factors influencing synthetic dye biodegradation

The efficiency of algae biosorption can be improved by optimizing operating conditions like pH, temperature, biosorbent dosage, contact time, initial dye concentration, and agitation [69;70].

The pH is an important factor in the adsorption processes of a dye, as it affects the ability and effectiveness of the adsorbent material and affects the surface charge of the adsorbent material, competition with ions, activity of the functional group, and the chemistry of pollutants [71]. The characteristics of the adsorbent, the adsorption process, and the dissociation of dye molecules can all be impacted by the pH of the aqueous medium. In general, anionic dyes bind better in acidic media, while cationic dyes bind better in basic media [72]. The biodegradation of dyes in an Aqueous medium is significantly influenced by temperature; High temperatures lead to changes in the active sites of the adsorbed material, which changes the viscosity and the effectiveness of adsorption. They also increase the possibility of the adsorbed material escaping from the active sites and ending up in the aqueous solution. In general, when the temperature increases, the amount of adsorbed dye decreases, which indicates that the biosorption process is exothermic [73, 71]. The dye absorption rate is impacted by contact time and is first fast; however, when the contact time approaches equilibrium, the absorption rate either ceases or declines, this is

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because a large number of open surface sites are available for absorption in the first phase. Following that, the open surface locations are occupied, and the solute molecules in the solid and bulk phases experience repulsive forces that make binding more challenging [74]. Another significant element that influences how well biosorbents remove or lessen dye is the dosage of the biosorbent (biomass concentration). Biosorption and biomass concentration are directly correlated, meaning that as the concentration of biomass rises, so do the number of biosorption sites, resulting in the efficient bioabsorption of dyes[75]. The initial dye concentration significantly impacts the adsorption process, with efficiency directly proportional to pollutant concentration. It indirectly affects dye removal efficiency by reducing or increasing binding sites on the adsorbent surface. In general, as the initial paint concentration increases, the percentage of dye removal usually falls because the adsorbent surface's adsorption sites get saturated[76].

Adverse effects of textile dyes on health and ecosystem

The unprocessed effluent generated by the textile sector is widely acknowledged as the main contributor to water contamination, it contains owing to its significant quantity and elevated concentrations of dyes and other persistent pollutants that pose a threat to the environment[77]. The discharge of dye pollutants has a detrimental impact on the aquatic ecosystem, as they obstruct sunlight and diminish the availability of oxygen. Consequently, it will impact the process of photosynthesis in aquatic environments, leading to a reduction in photosynthetic activity in aquatic plants as well as diminishing the capacity of aerobic microbes to digest organic matter. Furthermore, these compounds can have detrimental impacts on the food chain by infiltrating and accumulating inside it, ultimately reducing the diversity of aquatic creatures. [78]. Textile dyes in aquatic environments cause pH changes, increased oxygen demand, total organic carbon, biological oxygen demand, and suspended solids, causing adverse effects on aquatic creatures like fish and mollusks, resulting in higher rates of deformities and mortality [79]. Fish encounter several physiological and biochemical issues as a result of changes in water quality , Poisons and dyes can harm the nephrons in the kidneys, which can eventually result in renal failure. An in vitro study recently showed that applying hematoxylin dye to the kidney of species Cirrhinus mrigala fish, caused several changes, such as glomerulonephritis and tubular degeneration [80]. Additionally, these colors can interact with various liquid organic wastes, resulting in the production of very hazardous toxic aromatic complexes that are known to induce cancer and mutations[81]. Recent studies have shown that exposure to significant amounts of dyes over extended periods can have mutagenic, cytotoxic, and genotoxic effects on species, including humans. This exposure can result in allergy disorders, skin irritation, and dysfunction of organs [82].

Conclusions

The inappropriate disposal of liquid textile waste presents a significant risk to both human health and ecosystems. Conventional methods (both physical and chemical) are inadequate for achieving the necessary degree of wastewater treatment and disposal due to their exorbitant operational expenses and the production of undesirable hazardous byproducts. Scientists have initiated investigations into other approaches. There has been an increasing interest in biological treatments based on algae. These systems are highly regarded for their exceptional efficiency, environmentally friendly characteristics, and ability to utilize wastewater as a nutrient source, transforming it into industrially viable compounds. This method can serve as the optimal approach to efficiently and correctly eliminating developing contaminants, such as textile dyes, toxic metals, and other compounds. Nevertheless, this approach does have certain drawbacks, including reduced efficacy and the need for prolonged usage. Therefore, further investigation is required to identify appropriate algal strains that display accelerated growth rates and show economic feasibility and tolerance to pollution.

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Author Contribution

This review was written before. Z.H.O. and The author, Z.H.O., gave his approval to the final manuscript.

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