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Article

Unraveling the ecological footprint of textile dyes: A growing environmental concern

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Abstract: The textile industry, being a giant consumer of water and chemicals, uses synthetic dyes on a wide scale because of their low cost and wide color gamut. In contrast, synthetic dyes have shown great environmental hazards. A notable feature of textile dyes is their resistance to biodegradation, which contributes to long-lasting pollution in water, soil, and the atmosphere. The water body ecosystems are contaminated with dye-laden wastewater resulting from textile manufacturing. Photosynthetic activity is prevented, hence decreasing oxygen levels in water and drastically affecting aquatic life. Moreover, improper sludge disposal containing dyes leads to the degradation of soil quality, impacting plant health and microbial activities. Such pollutants can exhibit bioaccumulation in organisms, enhancing toxicity via the food chain and presenting serious health risks to humans, including carcinogenic effects and genetic malfunction. The paper reviews new developments related to ecologically friendly dyes, advanced wastewater treatments, and circular economies involving dye recycling and waterless dyeing techniques that are key to reducing the environmental impact of these dyes. Also needed is rigid enforcement of regulations coupled with the wider diffusion of sustainable technologies to minimize environmental damage in the textile industry and protect natural ecosystems and human health.

Keywords: textile dyes; environment; sustainability; ecological; wastewater

1. Introduction

Among the largest industries consuming water and chemicals, the textile dyeing industry is important in coloring [1–5]. In the last century, because synthetic dyes were cheaper and resistant, with a wide range of bright colors being produced, natural dyes were gradually replaced by synthetic dyes. However, accompanying the rapid growth of the textile industry is an emerging environmental problem created by the extensive use of artificial dyes [6–8].

Textile dyes are complex organic chemicals deliberately designed not to fade under light, water, and chemical actions; hence, they are intrinsically non-biodegradable and persistent in the natural environment [9–11]. Indeed, several million tons of dye-laden wastewater are directly discharged into rivers, lakes, and oceans annually, mainly in countries where textile industries are primarily located. Such wastewater generally contains a complex mixture of toxic pollutants, such as heavy metals, azo compounds, and aromatic amines, most of which are harmful to aquatic life and ecosystems [12,13].

The sad truth is that poorly treated or raw dye wastewater in the environment poses a severe hazard to water quality and biodiversity, besides affecting human health. First, these dyes can reduce the penetration of sunlight into the body of water, and due to this impact on the photosynthesis of the aquatic plants, an imbalance of the oxygen level in the inside water would affect the fish and other marine animals highly [14–16]. The residual content of dye elements in natural environments pollutes the atmosphere that afterwards bioaccumulates and biomagnifies through the food chain, thereby enhancing the magnitude of ecological hazards [17–21].

In this respect, the most important issues are the identification of the environmental impacts induced by textile dyes for the creation of sustainable alternatives to methods of wastewater management. This review discusses the ecological footprint of textile dyes, the pathways through which they enter into ecosystems, and the urgent need for developing and using eco-friendly dyeing processes/technologies within the textile industry.

2. Background of literature

The environmental impact of textile dyes has been a growing concern due to their widespread use and non-biodegradable nature. The literature reflects a historical shift from natural to synthetic dyes, primarily driven by cost and performance factors. However, this shift has resulted in significant ecological consequences. Synthetic dyes, which are used extensively in the textile industry, are designed to be resistant to biodegradation, leading to persistent pollution in water, soil, and air.

Research has identified several pathways through which textile dyes enter ecosystems, including wastewater discharge, improper solid waste disposal, and accidental spills. These dyes negatively impact aquatic life by reducing sunlight penetration, disrupting photosynthesis, and decreasing oxygen levels, which in turn affects biodiversity and water quality. Additionally, the toxic byproducts of dyes, such as heavy metals and aromatic amines, bioaccumulate in organisms, posing health risks to humans and animals.

Recent studies have focused on developing eco-friendly and biodegradable alternatives to synthetic dyes, alongside advancements in wastewater treatment technologies such as adsorption, bioremediation, and membrane filtration. Additionally, the circular economy model is being promoted in textile manufacturing to reduce dye waste through recycling and waterless dyeing techniques. Despite these developments, there is a critical need for stricter regulations and enforcement to mitigate the environmental damage caused by textile dyes.

3. Methodology

This review systematically examines the environmental impact of textile dyes by synthesizing existing research on their chemical composition, environmental pathways, and ecological consequences. Data were collected from a range of studies focused on synthetic dye pollution in water, soil, and air, with particular attention to the persistence of non-biodegradable dyes and their toxic byproducts. Key methodologies in the reviewed studies included chemical analysis of dye composition, wastewater discharge assessments, and environmental monitoring of affected ecosystems. The review also explores advancements in eco-friendly dye alternatives, wastewater treatment technologies, and sustainable manufacturing practices within the textile industry. A comparative analysis of regulatory frameworks across different regions was conducted to assess the effectiveness of environmental protection measures. Lastly, the paper integrates findings from various approaches to bioremediation, dye recycling, and waterless dyeing techniques to evaluate their potential for reducing ecological harm.

4. Chemical composition of textile dyes

Textile dyes are complex organic compounds that, giving color to fabrics, chemically bond with them. Most of the dyes used today are synthetic, petroleum-derived products that give vivid colors, durability, and resistance to many different external factors [22,23]. However, this chemical stability also makes many of these dyes toxic and non-biodegradable, thus contributing to long-term harm to the environment. **Table 1** provides the main types of textile dyes, their chemical nature, toxicity, and biodegradability.

Table 1. Different types of textile dyes with their composition, toxicity, and biodegradability.

Textile dyes	Composition	Toxicity and Biodegradability
Azo Dyes	The most prevalent class of synthetic dyes are azo dyes, which are distinguished by the presence of one or more azo groups (–N=N–) that give them their diverse array of vivid hues.	During decomposition, many of the azo dyes form aromatic amines, some of which are known to be carcinogenic. The complexity of structure imparts them resistance to biodegradation, hence they persist in the environment. Azo dyes are implicated to pollute water and thereby affect aquatic life.
Reactive Dyes	The reactive dye forms covalent bonds with fibers, especially those of cellulosic fibers such as cotton and wool. Such dyes are characterized by the presence of some reactive groups that would equally interact with hydroxyl groups among others in fabrics.	These reactive dyes are soluble in water, but in the process of their interaction with textiles, the lion's share of them undergo hydrolysis and accumulate in the wastewater of enterprises. Such dyes are resistant to biological destruction and thus may be toxic to aquatic organisms. The use in the dyeing process of salts and alkalis increases the damage.
Vat Dyes	The vat dyes are not water-soluble and must be reduced chemically to a soluble substance before application. After binding to the fabric they are then oxidized back into their insoluble state and are consequently extremely colorfast.	Such reduction and oxidation processes typically give rise to dangerous chemicals, like sodium hydrosulfite, which eventually release toxic wastewater. Vat dyes, with their insufficient degrading nature, remain in the environment for a longer period and cause pollution in both soil and water.
Disperse Dyes	Non-ionic, low-solubility colors called disperse dyes are applied to synthetic textiles like nylon and polyester. They penetrate the hydrophobic fibers when applied as small, scattered particles in water.	Toxic byproducts are released during the application of dispersed dyes because of the high temperatures and chemical carriers used. Environmental contamination results from these colors' difficult degradation in wastewater treatment facilities.
Acid Dyes	Acid dyes are water-soluble and can be used to color protein fabrics such as nylon, silk, and wool because they contain sulfonic acid groups.	Though brilliant, acid colors are very toxic to aquatic ecosystems, especially in their virgin state. They are only moderately biodegradable, whereas the salts and chemicals used in this process are not.

Textile dye wastewater is known for its complex composition, which varies significantly depending on the dyes and chemicals used during processing. Parameters such as Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), pH, and Total Dissolved Solids (TDS) are critical indicators of their pollution load and ecological impact [24–28]. These parameters provide insight into the level of organic pollution, chemical contamination, acidity/alkalinity, and solid residues, respectively.

Table 2 represents the properties of dye wastewater with their typical range and significance.

Table 2. Properties of textile dye wastewater.

Parameter	Description	Typical Range	Significance
BOD (mg/L)	Indicates the amount of biodegradable organic matter	100–400	High levels indicate potential oxygen depletion in receiving water bodies.
COD (mg/L)	Measures total chemical oxidation potential	500–2000	Reflects the total organic pollutant load.
pH	Acidity or alkalinity of the wastewater	6–10	Extreme pH can harm aquatic life and affect treatment processes.
TDS (mg/L)	Total concentration of dissolved solids	2000–5000	High TDS can lead to soil and water salinization.
Color (PCU)	Intensity of color in wastewater	300–2000	High color indicates the presence of dyes that reduce light penetration in water bodies.

5. Environmental pathways: How textile dyes enter ecosystems

The dyes utilized in textiles enter ecosystems through various channels due to the processes employed during their industrial manufacture. Inadequate treatment and disposal of wastewater containing dyes and solid waste products emanating from such industries are claimed to be a serious source of environmental pollution [29]. Further, spreading pollutants through water, soil, and air causes ecological environmental damage [30].

5.1. Entry through industrial wastewater

The major source of dye pollution consists of discharged wastewater with untreated or poorly treated dye residue from textile mills. During the dyeing process, about 10%–20% of the applied dyes do not get fixed onto the fabric but are wasted and washed out in water [31]. Most such wastewater containing dyes is directly discharged into local rivers, lakes, and oceans. In most developing countries where textile manufacturing is a major economic activity, because of weak enforcement or technology merely available in the past, industries sidestep the wastewater treatment regulations and directly poison the water bodies with harmful chemicals and dyes [32].

5.2. Improper disposal of solid waste

The sludge produced from dyeing is large in quantity, consisting of mixed chemicals such as heavy metals and unreacted dyes. Improper disposal of this sludge by landfilling or into open areas results in leaching into the soil, contaminating it with toxic compounds. Sometimes textile wastes, including residual dyes and post-treated fabrics, are incinerated. The result of this process is the release of toxic chemicals and particulate matter into the atmosphere, hence contributing to air pollution and subsequently to soil and water contamination as the pollutants settle [33,34].

5.3. Accidental spills and leakage

Dye container spills and leaks during transportation and storage lead to localized contamination in soils and nearby water bodies. In urban and industrial areas, stormwater may carry dyes from textile production sites into rivers and groundwater, further spreading the pollutants [35,36].

6. Distribution of textile dyes in soil, water, and air

Textile dyes spread into soil, water, and air after entering ecosystems through solid waste, wastewater, or unintentional spills, and they have varying effects on these environmental media.

6.1. Water

The most direct impact of dye pollution occurs on surface water bodies like rivers, lakes, and oceans. Dyes in water tend to reduce penetration depth; hence, it impacts the photosynthesis process of aquatic plants and algae [37]. This eventually results in limited oxygen levels in water, which might cause fish kills and harm other aquatic life forms. Sometimes dyes can enter groundwater systems through leaching from contaminated soils or seepage from untreated water waste. Groundwater contamination is particularly problematic as it can affect drinking water supplies and persist for long periods. Heavier dye molecules tend to settle in riverbeds and ocean sediments, where they can remain for decades. This poses long-term risks to benthic organisms (those living on the seafloor), which may absorb these pollutants, leading to bioaccumulation in the food chain [38,39].

6.2. Soil

In the event of leakage of dye-laden sludge during dumping, the dyes adsorb onto the soil particles and by that action are considered to pollute the soil. Because most of these dyes are synthetic, they are non-biodegradable and hence remain in the soil for a very long period, therefore reducing soil fertility and changing the physical and chemical properties of the soil. Toxic dyes interfere with the microbial flora of the soil, which reduces the activity of organisms essential for soil that take part in the decomposition of organic material and nutrient cycling. This could result in long-term plant growth damage and ecosystem health. Over time, dyes can leach into the soil and work their way to deeper layers, contaminating groundwater supplies. This process can be speeded up with rainfall or irrigation, most especially in those areas where the disposal of waste from the textile industries is poorly done [7,40,41].

6.3. Airborne

Some of the dyes, particularly those in high-temperature applications, can volatilize into the air. Airborne chemicals and particulates equally contribute to their contamination by depositing in water bodies or on land after sometimes traveling long distances [42]. Particles of textile dyes can be carried into the air by manufacturing processes or by disposal of wastes and, as dust, spread over industrial estates and beyond. It can settle on the nearby soils and in the respiratory systems of humans and animals upon inhalation, which poses health hazards [43].

7. Ecological impact of textile dyes

The widespread use of artificial dyes in the textile industry seriously affects ecology in water, soil, biodiversity, and food chains. The persistence and toxicity of many dyes are responsible for long-term environmental damage. The next section summarizes the significant ecological effects arising due to textile dyes.

7.1. Water pollution

Textile dyes are one of the main pollutants of water, especially in countries with weak enough legislation on wastewater discharging. Once the dye enters a river, a lake, or an ocean, it reduces sunlight input through the water, preventing photosynthesis in water plants and algae, hence disrupting oxygen balance and possibly hypoxia causing fish kills, and decreases in other aquatic species. The presence of dye as an environmental pollutant degrades the water quality of marine ecosystems, due to dyes containing toxic elements like heavy metals and aromatic amines, harmful to fish and crustaceans in marine life [44,45]. Bleaching may occur in coral reefs with reduced illumination, leading to disturbed ecological conditions due to the bioaccumulation of toxic dyes in marine organisms. Moreover, industrial runoff or infiltration of wastewater into the ground will leach the dyes into the soil to eventually contaminate supplies of groundwater, greatly endangering human populations and wildlife. Such contamination may persist in the groundwater for many years, further entangling the remediation process and raising costs to a high level [46].

7.2. Soil degradation

Land disposal of sludge or wastewater containing dye may significantly affect soil fertility and health. The main issue with the use of dyes is that, with a very high resistance to biodegradation, they adsorb soil particles and modify their composition in a nonreversible manner. Generally, toxic chemicals in dyes, especially heavy metals, disrupt the nutrient balance in the soil ecosystem impede plant growth, and decrease crop yields [47]. Organisms that are associated with nutrient cycling, decomposition, and overall soil health are threatened by dyes, including various soil microorganisms such as bacteria, fungi, and invertebrates like earthworms. This kind of pollution leads to disruption in microbial communities, diminishing their activities and further deteriorating the quality of the soil-soil which always has an impact on the ecosystems dependent on healthy soil [48,49].

7.3. Effect on biodiversity

Such organisms risk getting dyes through their gills or skin, a factor that can pose an aquatic life threat leading to respiratory disorders and resulting in reproductive failure or even death. Extreme conditions may cause the collapse of the entire food web in the water body due to such pollutants. Besides, high dye concentration can alter the pH of a water body and, at the same time, alter the temperature levels beyond those tolerable by life [50]. The presence of dyes further cuts down the penetration of sunlight in water, which is important for photosynthetic organisms in the form of aquatic plants and algae, translating to reduced oxygen production and disrupted food chains, as such organisms would have their base and producer plants affected.

Terrestrial plants growing in such soils are not spared either; this is manifested through stunted growth because of reduced nutrient availability and increased toxicity [51]. Besides this, toxic chemicals in textile dyes have adverse effects on aquatic and soil microorganisms. These chemicals decrease microbial activity in water, which hinders many useful processes that are part of ecological balance, such as decomposition and nutrient cycling. Similarly, the pollution of dyes in soils diminishes microbial diversity and abundance and further degrades soil health [52].

7.4. Bioaccumulation and bio-magnification

Bioaccumulation is the process where contaminants accumulate in aquatic organisms at rates faster than they can be excreted. A particular example of such contaminants is textile dyes, which are taken in by aquatic organisms through absorption and ingested with food or water [53]. Eventually, this may interfere with breathing, reproduction, and growth, critically depressing the populations of affected species, such as fish and molluscs. Furthermore, because contaminated organisms are consumed by predators, dyes tend to bio-magnify up the food chain. The higher the order of species, the greater the risk: For instance, those who rely on fish in dye-polluted waters may be exposed to toxic chemicals bio-accumulated within their bodies and could suffer from a whole array of serious health conditions, such as cancer, developmental problems, and neurological disorders [54].

The extensive use of synthetic textile dyes poses significant environmental challenges, particularly in aquatic ecosystems, due to their complex chemical structures, high stability, and resistance to biodegradation. These dyes, often released untreated or inadequately treated into water bodies during industrial processes, contribute to severe water pollution, including discolouration, altered light penetration, and depletion of dissolved oxygen [55,56]. The presence of toxic dye components and by-products affects aquatic organisms, causing mutagenic, carcinogenic, and endocrine-disrupting effects. Furthermore, synthetic dyes can disrupt microbial communities essential for maintaining ecological balance, hinder photosynthetic activity in aquatic plants, and accumulate in sediments, leading to long-term contamination [57,58]. These challenges indicate the urgent need for sustainable dyeing practices, effective wastewater treatment technologies, and eco-friendly dye alternatives to mitigate their impact on water ecosystems.

7.5. Textile dye production and disposal

The production and disposal of textile dyes contribute significantly to global ecological degradation through multiple channels, including the substantial carbon footprint associated with their synthesis and the depletion of natural resources. The manufacturing of synthetic dyes often relies on petrochemical derivatives, which require energy-intensive processes and release greenhouse gases, thus exacerbating climate change [59–61]. Additionally, the extraction of raw materials for dye production and the heavy use of water resources in dyeing operations further strain environmental systems [62]. When dyes are improperly disposed of, either through effluent discharge or landfill deposition, they persist in the environment, leading to contamination of soil, water, and air. This not only affects local ecosystems but also contributes to the global burden of waste, resource inefficiency, and pollution. The production of dyes relies heavily on non-renewable resources, while the lack of effective recycling and treatment systems worsens resource depletion and environmental harm. This highlights an urgent need for sustainable alternatives and closed-loop processes in the textile industry [63,64].

8. Human health implications of textile dyes

The widespread contamination of water and soil by textile dyes has serious consequences for human health. Many synthetic dyes contain toxic compounds that pose direct and indirect health risks to communities exposed to contaminated water, soil, and air. These chemicals can enter the human body through drinking water, food, air, and skin contact, leading to a variety of acute and chronic health issues [65]. Among the most concerning effects are the carcinogenic and mutagenic properties of some dyes, which increase the risk of cancer and genetic mutations.

8.1 Link between contaminated water/soil and human health risks

The textile dyes from unfixed industrial effluents reaching the water bodies pose a very high human health threat, more so in developing countries where the same river or groundwater is then consumed for drinking, cooking, and irrigation purposes [66,67]. It causes immediate health problems in the form of stomach and skin diseases. On the other hand, prolonged exposure to chromium and lead in groundwater may cause kidney dysfunction and neurological disorders due to heavy metals, especially in children. Besides, soil contamination by the dyes allows toxic elements to enter the food chain through crops, thus leading to chronic health problems for consumers and damaging the food production within that locality [68]. The emission of dye particulates into the air during manufacturing and waste incineration contributes to respiratory diseases for workers and residents around such areas where these activities occur. This, therefore, calls for improved approaches in the management of wastes emanating from the textile industries and strong regulatory measures [69].

8.2. Carcinogenic and mutagenic effects of some dyes

Synthetic dyes, more so those from azo dyes, are considered major health risks as they can induce carcinogenic or mutagenic activities. Azo dyes undergo degradation and release aromatic amine groups such as benzidine. These substances are responsible for many kinds of cancers like bladder, liver, kidney, and others. Long-term environmental exposure to these compounds enhances the risk of cancers in populations consuming such contaminated water or food. In addition, the mutagenic dyes have the potential to alter the DNA structure, which increases the chances of birth defects, developmental disorders, and problems in the reproductive system [70]. Workers in the textile industry are specifically exposed to great risks concerning cancer because of chronic exposure. Heavy metals such as chromium, cadmium, and mercury released from dyes can cause chronic disorders of the liver and kidneys, cardiovascular diseases, and immune dysfunction. Stringent regulatory steps must be invented in tandem with better waste management in the sector [71].

9. Regulations and policies governing textile dye usage and pollution

This wide-ranging impact of textile dye pollution has driven the establishment of limits by governments and supranational bodies that seek to minimize the effects on both ecosystems and human health. However, the stringency of such regulations is more often than not a function of the region's enforcement efforts, technological capabilities, and economic priorities [72]. The following section provides an overview of the existing regulations and regional and international efforts at controlling pollution from the textile industry.

9.1. Existing environmental regulations governing textile dye usage and discharge

The environmental and health effects of textile dyes have become a concern for several countries, which have begun regulatory mechanisms to manage the use of dyes and control wastewater discharge. In the European Union, the REACH regulation regulates hazardous chemicals, including textile dyes, and requires manufacturers to register and evaluate their environmental and health impacts. It also restricts or bans certain carcinogenic azo dyes. The EU Water Framework Directive enforces standards for water quality that force textile manufacturers to treat wastewater to reduce the amount of pollutants discharged into water bodies [73]. The Clean Water Act is in place within the United States to regulate the discharge of pollutants, such as textile dyes, through industrial effluent treatment to meet standards that the Environmental Protection Agency sets, and it regulates the Toxic Substances Control Act concerning assessing toxic chemicals in dyes. The Water Prevention and Control of Pollution Act, India, lays down standards for the discharge of pollutants from textile industries, hence effluent treatment plants [74,75]. Though regulatory mechanisms have been very inadequate in implementation, the Comprehensive Environmental Pollution Index keeps a close watch on industrial clusters with high textile production to regulate environmental standards [76]. These regulations show the effort undertaken globally in the improvement of health and environmental adverse effects caused by textile dyes, though enforcement and technological updates are critical to their effective implementation.

9.2. Regional and international efforts to control pollution from textile industries

Efforts to fight textile dye pollution have gone beyond the mere realm of national boundaries through several regional and international movements and programs that foster the implementation of sustainable practices, cleaner technologies, and a more stringent regulatory approach. The ZDHC is a program initiated by several global fashion and retail brands to eliminate all hazardous chemicals, including toxic dyes, from the complete textile supply chain before the year 2020 [77]. Indeed, the program will provide training and tools to the manufacturers about transitioning towards safer chemical alternatives and improved wastewater management practices. It focuses on the total elimination of carcinogenic and mutagenic dyes with minimal persistent pollutants. Further, the Stockholm Convention on POPs reaffirms this same belief in that it binds the signatory countries are EU states U.S., and even India to take action concerning certain toxic dyes used and disposed of to protect human and environmental health [78].

Regulatory frameworks and industry standards play a pivotal role in mitigating the environmental impact of textile dyes by setting guidelines for pollutant discharge, chemical usage, and sustainable practices. Policies such as the European Union's REACH regulation and the Zero Discharge of Hazardous Chemicals (ZDHC) program aim to limit the use of toxic chemicals and promote safe alternatives. Certifications such as OEKO-TEX® and GOTS promote the use of eco-friendly dyes and sustainable processing techniques, fostering greater accountability throughout supply chains. These frameworks also incentivize innovation by enforcing stricter compliance and penalizing non-compliance [79,80]. However, their sufficiency in driving meaningful change remains debatable. Challenges such as inconsistent global enforcement, gaps in addressing emerging contaminants, and the lack of stringent regulations in developing countries hinder widespread impact. Moreover, the rapid evolution of dyeing technologies and materials often outpaces regulatory updates, creating loopholes. While these frameworks provide a foundation for sustainable transformation, their efficacy relies on harmonized global standards, stricter enforcement, and complementary measures such as industry collaboration, consumer awareness, and financial incentives for green innovation [81,82].

In Asia, which is the main producing region of textiles, regional initiatives have also been set up. For example, the Water Pollution Prevention and Control Action Plan of China requires the adoption of cleaner production techniques, recycling of wastewater, and stronger limits on dye wastewater discharge [83]. Additionally, the Bangladesh Accord on Fire and Building Safety, recently extended following the Rana Plaza collapse, includes environmental safety guarantees that require each textile factory to treat wastewater and decrease chemical usage [84]. The final contribution is to the United Nations SDGs, where SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production) are being implemented through international organizations that strongly encourage such sustainability practices by governments and industries in the production of textiles to reduce water pollution by dyes and enhance resource efficiency through the introduction of the concept of the circular economy [85–87].

Consumer behavior and awareness about sustainable fashion are critical in reducing the ecological footprint of textile dyeing processes. By prioritizing eco-friendly choices, consumers can drive demand for sustainably dyed textiles, compelling brands to adopt greener practices and technologies [88,89]. Increased awareness about the environmental and health impacts of conventional dyeing processes encourages consumers to seek certifications like GOTS or OEKO-TEX®, which ensure safer and more sustainable products. Practices such as purchasing durable clothing, supporting slow fashion, and opting for garments dyed with natural or low-impact dyes promote reduced production volumes and resource conservation [90]. Additionally, consumer advocacy for transparency and accountability in supply chains can push manufacturers toward cleaner dyeing methods, such as waterless technologies or closed-loop systems [91,92]. Educational campaigns and social media also play a significant role in shaping perceptions and empowering consumers to make informed choices. By embracing sustainable purchasing habits, consumers empower systemic change and accelerate the industry's transition to environmentally responsible dyeing practices [93,94].

10. Innovative solutions and alternatives to reduce the impact of textile dyes

With greater awareness of the environmental and health hazards implored by textile dyes, lateral thinking has thrown up several solutions and alternatives that can help lighten the blow. Several solutions have been developed, from the development of environmentally friendly dyes, and improvements in wastewater treatment technologies, to a systematic engagement with the circular economy [95]. A few of these most promising approaches to the problem of pollution due to dyes are discussed in the section below.

10.1. Development of eco-friendly and biodegradable dyes

Another highly sustainable alternative to synthetic traditional dye is the development of eco-friendly biodegradable dyes. Natural dye, however, has a very long story in textile production: They are extracted from renewable resources, such as plants, fruits, and minerals; less toxic, but with a huge amount of raw material needed and, very often, mixed with harmful mordants [96]. On the other hand, biodegradable synthetic dyes achieved by green chemistry innovation are designed to degrade into harmless by-products with minimal persistence in the environment. In addition, microbial dyes produced by organisms such as fungi and bacteria provide a promising avenue toward sustainable dyeing through fermentation processes that contribute to lower manufacturing impacts. Altogether, these point toward a trend of increasing responsibility in dyeing practices within the textile industry [97].

Advancements in eco-friendly dye alternatives and sustainable dyeing technologies are transforming the textile industry by addressing its significant environmental challenges. Natural dyes sourced from renewable materials such as plants, algae, fungi, and agricultural by-products offer biodegradable and non-toxic options, reducing reliance on petroleum-based synthetic dyes [98,99]. Microbial dyes, produced through fermentation processes, present a novel avenue with high reproducibility and lower environmental impact [100]. Concurrently, innovative dyeing technologies are minimizing resource consumption and waste generation. Waterless dyeing methods, such as supercritical CO_2 dyeing, eliminate water use entirely, while digital printing reduces dye and energy waste. Enzymatic dyeing technologies leverage biocatalysts for precise and efficient dye application, significantly lowering chemical and energy requirements [101,102]. Additionally, advances in low-impact synthetic dyes with high fixation efficiency reduce dye runoff and improve wastewater quality. Closed-loop systems for dye recovery and reuse, coupled with advancements in wastewater treatment technologies, further enhance sustainability by curbing pollution. Collectively, these innovations signify a shift toward cleaner production practices and offer a promising pathway to mitigate the ecological footprint of textile dyeing while aligning with circular economy principles [103].

10.2. Wastewater treatment technologies

There is a pressing need to develop efficient and novel wastewater treatment technologies that take into consideration the environmental impact that the textile dyes are causing, focusing on the removal or degradation of such contaminants from industrial effluents before being released into the environment [104]. Adsorption methods are widely used; material like activated carbon demonstrates high effectiveness due to its big surface and adsorption capacity. Other adsorbents include agricultural wastes and nanomaterials under active research due to their sustainability. Bioremediation involves microorganisms such as bacteria and fungi. These have a biotransformation or detoxification of the synthetic dyes through metabolism [105]. Advanced oxidation processes involve highly reactive species transforming dyes into their nontoxic forms. However, these methods can be quite energy-intensive and costly. Besides, ultrafiltration and reverse osmosis are membrane filtration technologies, which effectively separate dyes from wastewater by making use of semi-permeable membranes that can allow clean water to pass through but retain the pollutants. These technologies are prone to fouling, which can reduce their efficiency. These technologies together contribute to a more sustainable approach to managing textile dye wastes [106–110].

In addition to widely used methods such as adsorption, bioremediation, and membrane technologies, several emerging technologies are gaining attention for their efficiency and sustainability in treating textile dye wastewater. Electrodialysis (ED) and Electrodialysis with Bipolar Membranes (EDBM) are advanced electrochemical processes that utilize selective ion transport to separate and recover valuable ions while reducing contaminants. Membrane Bioreactor (MBR) technology combines biological treatment with membrane filtration that offers high-quality effluent suitable for reuse [111–113]. Other innovative methods, including advanced oxidation processes (AOPs), hybrid systems, and electrocoagulation, are being explored for their ability to address the complex and variable nature of textile wastewater. These emerging technologies represent a promising dimension for achieving stringent environmental standards and resource recovery in wastewater management [114].

10.3. Circular economy in textiles: Recycling dyes and sustainable manufacturing

The textile circular economy model focuses on resource efficiency, waste reduction, and reuse, which considerably decreases the environmental impact caused by dyeing. One of the important approaches in this area is dye recycling from wastewater or used textiles by implementing various technologies such as nanofiltration, ion exchange, and electrochemical treatment that enable dye recovery and its reutilization with a significant reduction in fresh dye requirements and their associated pollution [115]. By contrast, waterless dyeing technologies such as supercritical CO_2 dyeing represent an environmental alternative since, in its supercritical state, carbon dioxide acts to transport dyes onto fabrics and radically reduces the use of water, using much less energy and chemicals. Digital printing further promotes sustainability in that dyes are applied directly to fabrics through computer-controlled processes generating minimal waste, water, and chemicals relative to analogue methods; moreover, production can be conducted to order, reducing unsold inventory [116,117]. Secondly, sustainable manufacturing of textiles should invest in the wide usage of organic fibers and eco-friendly chemicals to generally reduce the environmental footprint of the industry by the involvement of certificates like GOTS and OEKO-TEX that guarantee the observation of environmentally friendly standards. Put together, these methods are indicative of a commitment to a more sustainable and circular textile industry [118,119].

One of the significant challenges posed by the circular economy of textiles is the recovery of inorganic salts, such as sodium chloride and sodium sulfate, from treated dye wastewater during the final treatment stages. These salts, often present in high concentrations, are critical for various industrial applications, including textile dyeing processes [120]. However, their effective recovery requires overcoming technical and economic barriers. Advanced technologies such as precipitation methods have shown promise in selectively removing and recovering these salts by converting them into insoluble compounds, which can then be purified and reused [121]. Furthermore, emulsion liquid membrane (ELM) technology has emerged as a highly efficient approach, utilizing liquid membranes to encapsulate and extract specific ions or compounds from complex wastewater streams [122]. This method not only enhances recovery efficiency but also reduces chemical consumption and secondary waste generation. Capacitive deionization (CDI), often employed in combination with membrane filtration systems, leverages electrochemical techniques to remove and concentrate salts from wastewater, enabling their reuse while producing high-quality treated water [123]. When integrated with other sustainable processes, such as reverse osmosis or nanofiltration, these technologies form hybrid systems capable of achieving high recovery rates and meeting the stringent requirements of zero-liquid discharge (ZLD) frameworks [124–126].

Advancements in resource recovery support the principles of a circular economy by facilitating the reuse of vital raw materials, decreasing reliance on virgin resources, and lowering the environmental impact of textile production. As research progresses, the integration of these innovative solutions into large-scale industrial operations holds the potential to revolutionize wastewater management and contribute to a more sustainable and eco-friendly textile industry.

11. Conclusion

Most of the ecological impacts are brought about by textile dyes, which highly affect water, soil, and even biodiversity. Mainly synthetic textile dyes are non-biodegradable, toxic, and tend to persist in the environment for years. Since most entry routes of ecosystems include untreated industrial wastewater improper waste disposal and accidental spilling, this results in extensive pollution. In aquatic ecosystems, these dyes interfere with the photochemical process, decrease oxygen levels, and disrupt life in water, hence promoting losses in biodiversity. Additional contamination of the soil impairs fertility and has further deleterious implications for plant and microbial life.

The development of eco-friendly dyes, new technologies for the treatment of wastewater, and regulatory mechanisms to control textile dye pollution are therefore some of the mitigants pursued. Environmental sustainability could be ensured by using biodegradable dyes, bioremediation techniques, and waterless dyeing technologies. However, such measures need to be implemented with far more rigors and more deeply disseminated to combat the rising environmental menace caused by textile industries. Conclusion As bad as the environmental impacts of textile dyes are, textile dyes are quite vital for the manufacturing process of fabrics. What is needed immediately is a shift toward greener alternatives through improved legislation and systems for treating wastewater in ways that minimize the ecological impact of textile dyes on ecosystems and human health.

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