

Environmental and Toxicological Implications of Dyes: A Mini Review

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Abstract

Synthetic dyes are extensively used in industries – such as textiles, leather, paper, and food processing – due to their vibrant colors and high chemical stability. However, the large-scale release of dye-containing wastewater has become a significant environmental and health concern. Owing to their complex chemical structures, most synthetic dyes are highly resistant to biodegradation, resulting in their long-term persistence in aquatic and terrestrial ecosystems. Their accumulation in water bodies reduces light penetration and dissolved oxygen levels, negatively impacting aquatic life and disturbing ecological balance. Furthermore, many synthetic dyes and their degradation by-products are associated with toxic, mutagenic, and carcinogenic effects, posing serious risks to both environmental and human health. Azo dyes, in particular, can undergo reductive cleavage to produce aromatic amines, several of which are recognized as hazardous to human health. This mini review summarizes the major classes and sources of synthetic dyes, discusses their environmental fate and toxicological implications, reviews the existing regulatory framework, and highlights the need for sustainable strategies to minimize dye contamination and its associated risks.

Keywords: Dyes, toxicity, environmental pollution, industrial wastewater, ecotoxicity

INTRODUCTION

One of the biggest industrial pollutants and a key cause of water contamination is dyes [1]. Water quality is negatively impacted when a variety of industries release dye-containing wastewater into bodies of water. These sectors include food processing facilities, tanneries, paper and pulp mills, distilleries, electroplating facilities, textile manufacture, and dye production [2]. Textiles, paint, food, pharmaceuticals, cosmetics, and thermoplastic materials all make use of synthetic dyes. The textile sector uses more than 10,000 tons of dye annually [3]. Textile dyes account for approximately 90% of the global consumption of synthetic dyes. The textile dyeing process requires large volumes of water, often reaching around 200 tons of water per ton of textile produced, and involves the extensive use of potentially hazardous chemicals. Textiles are dyed or printed using over 10,000 different types of dyes.

These dyes are thought to find their way into industrial wastewater in significant amounts during processing. According to reports, the textile sector releases around 100 tons of dyes into rivers and other water bodies annually, raising major ecological and environmental issues [2].

Wet processing operations in the textile industry require large volumes of water and a wide variety of chemical additives, making the sector one of the major generators of industrial wastewater [3]. These chemicals include inorganic salts, polymers, and numerous organic compounds that serve different functions during textile processing. Among the various pollutants present in textile effluents, dyes are of particular concern because they impart

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intense color to wastewater, making contamination clearly visible even at very low concentrations [4]. It is estimated that more than 100,000 commercial dyes are available worldwide, with annual production exceeding 700,000 tons. The complex molecular architecture of synthetic dyes provides excellent color fastness and resistance to degradation by light, water, and many chemical agents. Consequently, these compounds are often difficult to remove from wastewater using conventional treatment methods [5]. Textile dyes encompass several chemical classes, including acidic, basic, disperse, azo, diazo, anthraquinone, and metal-complex dyes. Conventional aerobic biological treatment systems, commonly employed in municipal wastewater treatment plants, are generally ineffective in achieving complete color removal from textile effluents, allowing colored wastewater to persist as a significant environmental challenge [1]. When discharged into natural water bodies, dye-containing effluents reduce the penetration of sunlight through the water column, thereby limiting photosynthetic activity and decreasing dissolved oxygen levels. These changes disrupt the ecological balance of aquatic ecosystems and adversely affect the survival and functioning of aquatic organisms. Textile dyes are classified as hazardous pollutants due to their poisonous, mutagenic, and carcinogenic characteristics. Once discharged into the environment, these dyes can remain for a long time and enter food chains, resulting in biomagnification. As a result, species at higher trophic levels collect more of these pollutants than those at lower levels [6–8]. Textile dyes are widely used and represent considerable dangers to human health and ecological systems. There are currently over 10,000 distinct dyes used in the textile industry, with azo dyes accounting for over 70% of the total. These dyes are mostly synthetic and have complicated chemical structures, making them difficult to breakdown. This chapter looks at the negative consequences of textile dyes on human health and the environment, as well as several remediation options for their removal and management. As a result, surface water becomes contaminated, which influences people's health. According to reports, industrial effluents contaminate the air, water, and soil, increasing the risk of sickness and ultimately shortening life expectancy in affluent nations [9, 10].

DYES CLASSIFICATION

Dyes can be categorized using several criteria, including their chemical structure, method of application, ionic nature, and affinity towards different textile fibers. Among these, classification based on the application method is the most widely adopted because it reflects the interaction between dyes and textile substrates as well as their practical use in industrial dyeing processes. The major classes of dyes are illustrated in Figure 1 [11, 12].

Direct Dyes

Direct dyes are primarily used for cellulosic fibers and are valued for their ease of application without the need for mordants or additional chemical fixation. They comprise several chromophoric groups, including azo, stilbene, phthalocyanine, dioxazine, and, to a lesser extent, anthraquinone, formazan, quinoline, and thiazole derivatives. These dyes offer an extensive color range and are relatively economical for textile processing. However, their resistance to repeated washing is generally lower than that of reactive dyes. Consequently, reactive dyes have gradually replaced direct dyes in many applications requiring superior wet fastness and durability on cellulose-based fabrics.

Reactive Dyes

Reactive dyes are among the most extensively used dyes for cotton and other cellulosic textiles because they provide excellent wash fastness and color durability. These dyes are water-soluble and predominantly anionic in nature. Their distinctive feature is the presence of reactive functional groups, often containing halogen atoms, which form stable covalent bonds with hydroxyl groups present in cellulose fibers during the dyeing process. This permanent chemical bonding significantly improves dye fixation and minimizes color loss during laundering. Although primarily developed for cotton, reactive dyes are also suitable for dyeing protein fibers, such as wool and silk, as well as polyamide fibers including nylon. Owing to their high fixation efficiency and durable color performance, reactive dyes have become one of the most widely employed dye classes in the textile industry [10, 13].

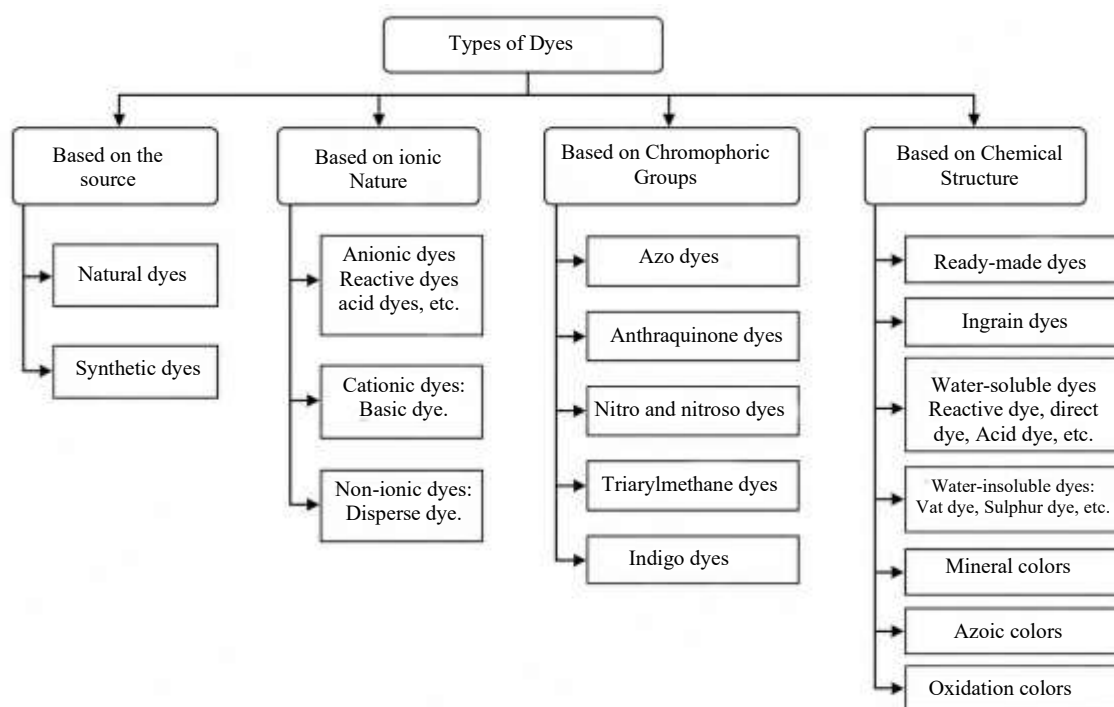


Figure 1. Dyes classification.

Basic Dyes

Basic dyes, also referred to as cationic dyes, possess a positive charge that enables strong affinity towards negatively charged fibers such as acrylic and jute. They are readily soluble in alcohols, including methylated spirits, but exhibit limited solubility in water. Their dyeing behavior is primarily governed by the cationic groups present in their molecular structure [10, 14].

Vat Dyes

Vat dyes are mainly used for dyeing cellulosic fibers, particularly cotton, owing to their exceptional resistance to washing, bleaching, and light. Their outstanding fastness is attributed to their water-insoluble nature after the dyeing process. These dyes are seldom applied to synthetic fibers because of their low affinity and poor diffusion into such materials, resulting in limited color depth. Consequently, other dye classes are generally preferred for synthetic textiles [15].

Disperse Dyes

Disperse dyes are primarily used for coloring hydrophobic thermoplastic fibers. These dyes are sparingly soluble in water and, therefore, require dispersing agents for uniform application. They exhibit low affinity towards fibers and are commonly based on azo, anthraquinone, or diphenylamine compounds. Disperse dyes are widely employed for dyeing acetate, triacetate, polyester, nylon, and acrylic fibers [10].

Acid Dyes

Acid dyes are water-soluble, anionic dyes that are generally applied in an acidic dye bath using acids such as formic or acetic acid. Most are sulphonic or carboxylic acid salts and readily bind to protein and polyamide fibers through ionic interactions, supplemented by hydrogen bonding and van der Waals forces. Their molecular structures vary considerably, with some containing metal complexes, resulting in a wide range of color shades and fastness properties. The presence of sulphonate groups imparts water solubility and facilitates bonding with amino groups in fibers such as wool and nylon. Consequently, acid dyes are extensively used for dyeing wool, silk, and nylon [10, 16].

Mordant Dyes

Mordant dyes, also known as chrome dyes, are chromium-based dyes that exhibit low natural affinity for textile fibers. Their fixation requires the use of mordants, which act as chemical binding agents between the dye and the fiber. These dyes are mainly employed for coloring natural protein fibers, as well as nylon and modacrylic fibers [10, 17].

Sulfur Dyes

Sulfur dyes are widely used to produce black and dark brown shades, particularly on cotton fabrics. Like vat dyes, they are insoluble in water and require reduction in an alkaline medium before application, followed by oxidation to develop the final color. Their molecular structure contains disulfide linkages that contribute to their dyeing properties. Besides textiles, sulfur dyes are also used for coloring silk, leather, and paper [10, 18].

Azoic Dyes

Azoic dyes represent the largest class of synthetic dyes, accounting for nearly 70% of industrial dye production, with an estimated annual global output of approximately one million tonnes. More than 2,000 commercial azo dyes are available and are widely used in the textile, leather, cosmetic, pharmaceutical, paper, paint, and food industries. Their defining characteristic is the presence of one or more azo ($-N=N-$) linkages connecting aromatic or heterocyclic rings. Based on the number of azo bonds, they are classified as monoazo, diazo, or triazo dyes. Azoic dyes are generally water-insoluble color-forming compounds that are produced directly on the fiber through coupling reactions involving diazonium salts and coupling components. This dyeing process typically requires separate impregnation and development baths, making them suitable for dyeing cotton, nylon, and polyester fabrics [10].

Anthraquinone Dyes

Anthraquinone dyes constitute one of the major classes of synthetic textile dyes, second only to azo dyes in commercial importance. They produce a broad range of colors across the visible spectrum and possess excellent chemical stability owing to their fused aromatic ring structure, which makes them highly resistant to degradation [10].

IMPACT OF TOXIC DYES ON ENVIRONMENT

The textile industry generates large quantities of wastewater containing a complex mixture of organic and inorganic pollutants. During the dyeing process, a considerable fraction of dyes remains unfixed to the fibers and is discharged with effluent, making textile wastewater highly colored and chemically contaminated. Water consumption and wastewater generation vary with the type of textile being processed. Cotton, one of the most widely used natural fibers, is commonly dyed using azo dyes, which are highly resistant to conventional treatment methods because of their stable azo ($-N=N-$) linkage. In addition to dyes, textile effluents often contain high concentrations of salts that inhibit the growth of beneficial microorganisms by creating osmotic stress, leading to plasmolysis and reduced microbial activity. The discharge of untreated textile wastewater also alters key water quality parameters, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), total suspended solids (TSS), and pH, thereby posing a serious threat to aquatic ecosystems and soil health.

Water pollution poses a serious threat to aquatic and terrestrial life since it can contaminate them with harmful substances and cause illness. It may add smell and change the quality of the water. If wastewater from textiles is not reintroduced into the environment after being appropriately cleaned, it can add metals (Cr and Cd), organochlorine substances that fish in receiving streams may bioaccumulate. When ingested, these fish may be dangerous to humans. Degraded starch and leftover dye produced reduces the water quality, making it unsafe to drink by giving water, a hue and smell. Additionally, hot effluent influences the dissolved oxygen (DO), which has an impact on the watery habitat of living creatures in these kinds of streams. The sunlight that enters the water is absorbed and reflected by the effluents, which decreases photosynthesis, dissolved oxygen level and affects entire oceanic biota. Additionally,

depending on the concentration and duration of exposure, they may have either acute or chronic impacts on organisms. When colored wastewater, which occasionally contains pigments visible to the naked eye (<1 ppm) is discharged into surface or groundwater bodies, it lowers the water's content of oxygen that has been broken up (Ali, 2010). It increases the values of physical, chemical, and biological parameters, including total dissolved solids (TDS), total nitrogen (TN), total phosphorus (TFP), and non-biodegradable organic substances. This information was reported on chemical oxygen demand (COD) and biochemical oxygen demand (BOD). However, wastewater has a pH that varies a lot and becomes high due to metals like zinc (Zn), arsenic (Ar), and chromium (Cr).

Environmental standards should be transformed to support significant natural aims globally, as natural challenges often cross-national borders and affect people from various countries. Exporters may face higher manufacturing costs due to different importers' standards. Specific requirements demand different strategies to prevent using natural benchmarks as a form of protectionism. Modifying environmental standards can help address global ecological challenges that affect people across boundaries. Exporters may face higher manufacturing costs due to different importers' standards. Specific requirements demand different strategies to prevent using natural benchmarks as a form of protectionism.

TOXIC IMPACT OF DYES ON HUMAN HEALTH AND PLANTS

The widespread use of synthetic dyes poses significant risks to both human health and the environment. Workers involved in textile dyeing and finishing are particularly vulnerable because of prolonged exposure to dyes and associated chemicals. Inhalation of reactive dye particles is one of the primary occupational hazards and may lead to respiratory sensitization, resulting in symptoms such as coughing, wheezing, sneezing, itchy eyes, and asthma-like conditions. Repeated exposure can also trigger immune-mediated allergic responses.

Direct contact with dye-containing effluents may cause skin and eye irritation, while textile workers frequently report occupational disorders such as contact dermatitis, allergic conjunctivitis, rhinitis, and occupational asthma. These reactions are often associated with the formation of antigenic complexes between reactive dyes and human serum albumin, which stimulate immunoglobulin E (IgE)-mediated histamine release. Certain azo dye intermediates, particularly benzidine-based compounds, have also been linked to an increased risk of bladder cancer. Moreover, several azo dyes and their degradation products exhibit toxic, mutagenic, genotoxic, and carcinogenic effects in both humans and animals.

According to Shindhal et al. (2021) [19], Solvent Yellow 14, is a member of the family of azo-lipophilic complexes that are frequently utilized in industrial settings. When they are present in human and animal organisms, the gut flora naturally converts them into carcinogenic aromatic amines. Basic Red 9 dye is very poisonous and carcinogenic, breaking down into carcinogenic aromatic amines under anaerobic conditions. It can cause skin irritation, cancer, allergic dermatitis, and genetic abnormalities.

Textile dye effluents contain hazardous compounds that can adversely affect humans, animals, plants, and aquatic ecosystems. Experimental studies have shown that Red-S3B azo dye is highly phytotoxic, significantly inhibiting the growth of young wheat seedlings. However, a microbial consortium comprising *Shewanella* sp. and *Aspergillus terreus* NIAB-FM10 achieved complete decolorization of Red-S3B (500 mg L^{-1}) within four hours and improved shoot and root growth, as well as biomass, in 30-day-old wheat plants [19].

The persistence of synthetic dyes in the environment is largely attributed to their complex chemical structures, which resist biodegradation. Many dyes, particularly azo, anthraquinone, and triarylmethane dyes, exhibit toxic, mutagenic, and carcinogenic properties and may remain in the environment for several decades. Their environmental persistence and toxicity depend on molecular structure, chemical reactivity, and concentration, with the potential for biomagnification through the food chain, thereby posing greater risks to organisms at higher trophic levels [20].

Azo dyes have received particular attention because they constitute the largest group of synthetic dyes and many members can undergo reductive cleavage to form aromatic amines such as benzidine, dimethoxybenzidine, and dimethylbenzidine. These metabolites can interact with DNA through reactive intermediates, leading to mutagenic and carcinogenic effects. Consequently, prolonged exposure to azo dyes and their degradation products has been associated with an increased risk of cancer and other adverse health outcomes [21, 22].

The release of untreated dye-contaminated wastewater into aquatic environments also threatens food safety, as toxic compounds can accumulate in aquatic organisms and enter the human food chain. Exposure to these contaminants has been associated with nausea, hypertension, skin lesions, organ damage affecting the liver, kidneys, brain, and central nervous system, and, in severe cases, mortality. In addition, several azo dyes may cause acute and chronic toxic effects, including skin and eye irritation, allergic dermatitis, respiratory distress, gastrointestinal disorders, and tissue damage. Water-soluble azo dyes become particularly hazardous after metabolic activation in the liver, while sweat and moisture can enhance dermal absorption of aromatic amines, increasing the risk of systemic toxicity [23, 24].

Textile dyes can cause different types of diseases, e.g.:

- *Nervous System*
 - o Block intracellular enzymes that are part of the central nervous system.
 - o Metals that are toxic affect neurological systems.
- *Liver*
 - o Hepatocarcinoma.
 - o Can elevate serum levels of alkaline phosphatase (ALP) and gamma-glutamyl transferase (GGT), indicating impaired liver function or hepatocellular damage.
- *Kidney*
 - o Reticular cell sarcoma.
 - o Kidney damage caused by heavy metals.
 - o Urothelial carcinoma.
- *Skin*
 - o Skin inflammation.
 - o Ocular Allergy.
 - o Allergic Rhinitis or Hay Fever.
 - o Occupational bronchial asthma.
 - o Other allergic reactions.
- *Enzymatic System*
 - o Enzyme inhibition.
 - o Arylamine Synthesis/Primary Aromatic Amine Generation.
 - o Block enzymes like glutathione reductase and disrupt cellular redox balance.
- *Human Chromosomes*
 - o Induce significant genotoxic effects by causing DNA damage and chromosomal abnormalities.
 - o Intercalate into the DNA double helix and interact with RNA, thereby increasing the risk of mutations and genetic instability.
 - o Growing the number of micronuclei.
 - o Carcinogenic.
- *Reproductive System*
 - o Spermatozoa cells are affected by cytotoxicity.
 - o Tests weight reduction.
 - o Reduction in glucose and ovarian protein.

CONCLUSION

The textile, paper, pulp, tannery, cosmetic, and leather sectors are typically the ones that release dyes. When these dyes are discharged into the environment, they are typically harmful and cause hazards to

humans. Ecological balance and human health are negatively impacted by the materials and chemicals used in the production of textiles. Analyzing the chemicals and other materials in textiles is crucial, and further research on this topic is required. Hazardous chemicals may be present in clothing items. We must increase public knowledge of the possibly dangerous textiles. Dyes are poisonous and long-lasting; they cause substantial environmental and public health problems. Their presence in water and soil systems has negative consequences on aquatic life, ecosystems, and human health. This assessment emphasizes the critical need for effective control methods, new treatment technologies, and long-term practices to limit dyes' environmental impact. Addressing these issues is critical to preserving natural balance and guaranteeing public safety.

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