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# Bright Colours, Dark Consequences: Synthetic Dyes Poisoning Aquatic Life

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Synthetic dyes are silently poisoning water, turning vibrant colours into an environmental catastrophe. Once valued for their vivid hues and durability, these dyes, especially from textile industries, now rank among the most insidious aquatic pollutants. Though present in trace amounts, their impact is vast: untreated dye-laden wastewater pours into rivers and lakes, choking ecosystems, depleting oxygen, and blocking light essential for aquatic life. Fish exposed to these pollutants suffer cellular damage, nutrient deficiencies, and alarming behavioural changes, while algae which is vital to ecosystem health-experience stunted growth and pigment loss. These dyes are chemically resilient, resisting natural breakdown, accumulating through the food chain, and even reaching our tables. Azo dyes, particularly notorious for their toxic effects, linger in water, unaffected by typical treatments, and introduce carcinogenic risks to both wildlife and humans. This unchecked pollution is more than an aesthetic issue; it is an environmental emergency that demands advanced wastewater treatment solutions to stem the flow of toxic colours into water sources.

**Keywords:** Ecotoxicity, Persistence, Carcinogens, Biomagnification

## Introduction

Aquatic pollution is becoming an increasingly critical issue. With the rapid expansion of industries like chemical manufacturing, pharmaceuticals, and agriculture, various chemical substances-including pesticides, steroid hormones, antibiotics, and dyes-are entering water ecosystems. Synthetic organic dyes are often overlooked as environmental contaminants; however, they are now categorized as micropollutants because they are present in only trace amounts (ng/L to µg/L) in aquatic environments. Despite these low concentrations, dyes are pervasive due to their large-scale production and extensive range of applications (Zuccato *et al*., 2005; Pereira *et al*., 2012).

In 1865, William Perkin discovered mauveine, the first synthetic organic dye, sparking a transformative shift in the dyestuff industry and launching synthetic dye production worldwide. By the early 1900s, Europe dominated global dyestuff production, but today, China and India lead in production. However, India is a significant contributor to textile waste in South Asia, with Maharashtra and Gujarat producing 90% of the country's dyes due to abundant raw materials and a strong textile sector. Jodhpur hosts the largest hub of textile dyeing and printing facilities. Numerous chemicals used in this industry pose environmental and health risks. Dyes in textile wastewater are major pollutants, contributing to global water pollution issues tied to untreated effluent discharge and the release of harmful chemicals into water bodies. This pollution drastically reduces oxygen levels in water due to hydrosulphides and obstructs light penetration, which harms aquatic ecosystems. About 40% of globally used dyes contain chlorine compounds, many of which are carcinogenic. Additionally, textile effluents often contain heavy metals that are non-biodegradable.

Untreated or insufficiently treated textile wastewater can harm both aquatic and terrestrial ecosystems, posing long-term health risks and affecting biodiversity (EFSA *et al.*, 2017).

Synthetic organic dyes form the largest category among all colouring substances, with estimates suggesting that over 100,000 varieties are commercially available worldwide, contributing to an annual production volume exceeding 1 million tons. These dyes are extensively utilized in industries such as textiles, tanning, printing, and paper, and have also found roles in pharmaceuticals, cosmetics, and food processing. Additionally, certain synthetic organic dyes act as pharmacologically active substances (PASs) and are employed in both human and veterinary medicine. The large-scale production and widespread use of these dyes generate vast amounts of coloured wastewater and various forms of industrial waste (Bamfield *et al.*, 2001; Alia *et al.*, 2010).

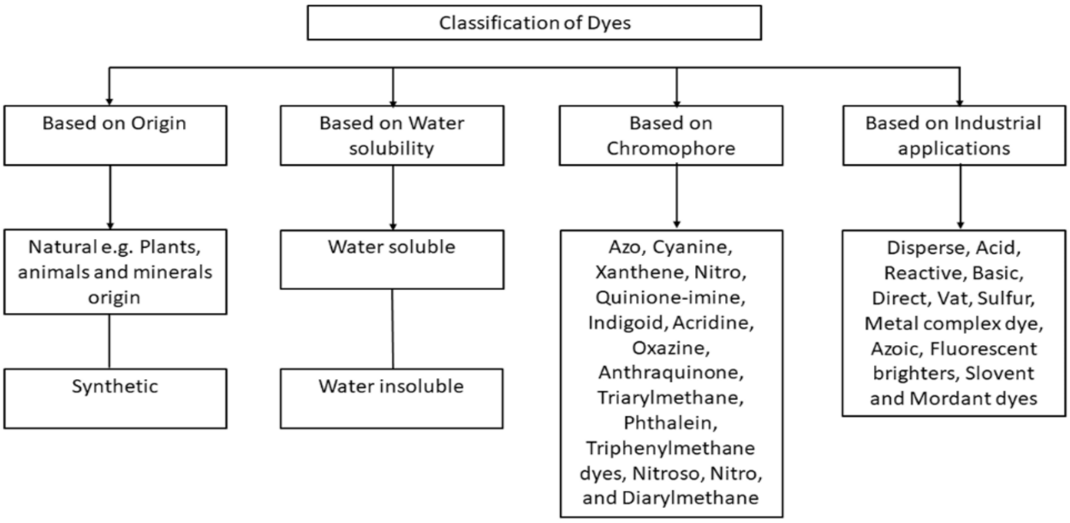
The textile industry is a significant contributor of dyes to water systems; depending on the fabric and dye type, dye wastage during the dyeing process ranges from at least 5% upto 50%, resulting in approximately 200 billion Liters of dyed wastewater annually. Furthermore, certain synthetic organic dyes are resistant to or cannot easily biodegrade, complicating their removal through standard sewage treatment plant (STP) processes. Research has also demonstrated that some of these dyes possess toxic properties, including carcinogenic, allergenic, and dermatitis effects, raising concerns about their safety in production and use (Kant *et al.*, 2012; Zaharia *et al.*, 2012).

## Textile Dyes

Dye is a substance used to impart colour to textiles, paper, leather, and other materials such that the colouring is not readily altered by washing, heat, light, or other factors to which the material is likely to be exposed. Textile dyes are synthetic chemical compounds with aromatic structures that are difficult to biodegrade due to their xenobiotic properties. These dyes can negatively impact aquatic environments by reducing light penetration, which interferes with photosynthesis in water plants. Currently, most textile dyes are synthetic and are primarily produced from coal tar and petroleum-based intermediates, available in forms like powders, granules, pastes, or liquid dispersions. To meet the demands of advancing technologies, new fabric types, detergents, and dyeing machinery as well as to address environmental issues, new dyes are regularly developed. Seasonal shifts in product demand also influence the dye industry, requiring industrial textile dyes to adapt to changing technical needs. With the shift in the textile industry from high-cost cotton fabrics to more durable synthetic fibres, dye usage patterns have evolved. Polyester now represents a significant portion of dye consumption, increasing demand for disperse dyes specifically suited for polyester. Additionally, sulfonated vinyl reactive dyes, which contain azo chromophores (N=N), make up about 60% of the dyes used in textiles. These dyes are water-soluble and often appear in high concentrations in wastewater, with up to 50% of the dye remaining unfixed on fibres and ultimately discharged as waste (Benkhaya *et al.*, 2020).

## Types of Textile Dyes

Dyes are organic compounds that dissolve in water and contain three key functional groups: the chromophore, responsible for colour; the auxochrome, which enables dye fixation; and the matrix, which includes the other atoms in the molecule. Dyes are generally classified by their origin into two types: natural and synthetic. Natural dyes are categorized by their origin, which can be plant-based, animal-derived, or mineral-based. On the other hand, synthetic dyes are grouped according to their chemical structure, including azo, phthalocyanine, indigo, anthraquinone, aryl methane, and heterocyclic dyes. Dyes can also be classified based on properties such as water solubility, chromophore presence, and industrial uses. For instance, acid, direct, mordant, basic, metal complex, and reactive dyes are water-soluble, whereas azoic, disperse, vat, and sulphur dyes are water insoluble (Orts *et al.*, 2018; Berradi *et al.*, 2019)




Source: Mehra *et.al* (2021)

## Characteristics and Impacts of Synthetic Dyes

Synthetic dyes, largely derived from petrochemicals, are popular in textiles because they offer rich, consistent colours across many fabric types, a wide range of shades, durability, and easy handling with relatively low energy requirements. However, these dyes come with environmental downsides. During textile processing, up to 15% of dyes do not bond to fibres and end up in wastewater, while dyeing and finishing stages consume vast amounts of water, leading to ongoing wastewater discharge.

This wastewater is laden with pollutants like chlorinated compounds, heavy metals, and formaldehyde. Even after treatment, harmful substances often remain, contaminating water, soil, air, and plants. These pollutants do not just damage ecosystems but linked to serious human and fishes' health risks as well. The widespread use of synthetic dyes, while convenient, thus raises significant ecological and health concerns.

**1. Impact on Fish:** A comparative toxicological study of textile dye wastewater (both untreated and treated) on the freshwater fish *Gambusia affinis* revealed a significant decrease in mortality rates and cytotoxic effects on red blood cells (RBCs). It was observed that there was a reduction in RBC counts, as well as changes in their shape (poikilocytosis) and size variation (Soni *et al.*, 2006).

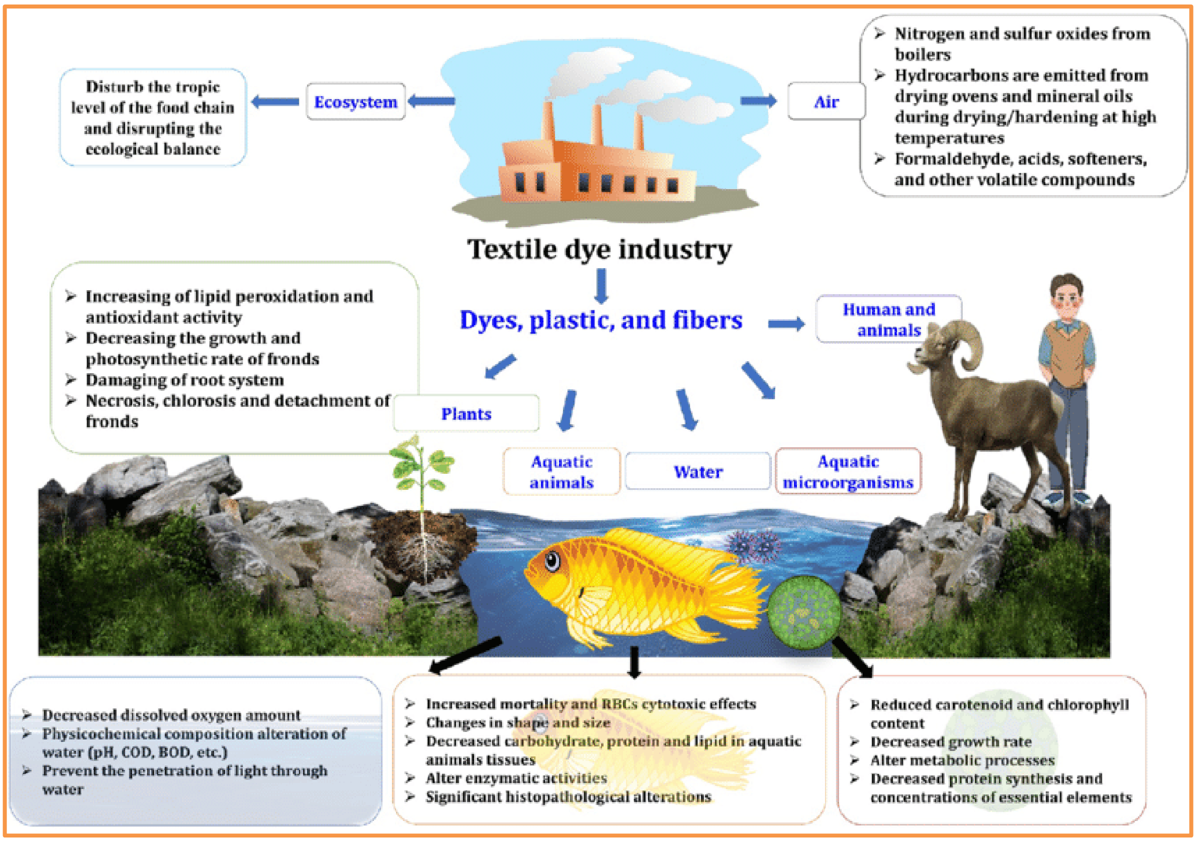
Another study conducted by Karthikeyan *et al.*, 2006 on *Mastacembelus armatus*, an edible freshwater fish rich in protein, exposed to textile effluents showed alterations in the ionic regulation of tissues such as the liver, kidney, and muscles. Specifically, there was a decrease in sodium and chloride ion concentrations, while potassium, calcium, and magnesium ion concentrations increased. The impact of textile industry effluents on the teleost fish *Poecilia recticulata* resulted in abnormal behaviors, including erratic swimming, hyper-excitation, rapid opercular movement, and the development of thick mucus coverings. Histopathological changes included the enlargement of the primary gill bar, detachment of the secondary gill bar, disintegration of intestinal villi, and the infiltration of hemocytes into the lumen (Selvaraj *et al.*, 2015).

A similar study conducted by Amte *et al.*, 2013 on the hematological parameters of the freshwater fish *Oreochromis mossambicus* exposed to textile dyeing industry effluent indicated histological changes in the liver, including hyperemia, necrosis, and degeneration.

Textile dye effluents also impacted the nutritional value of the freshwater female crab *Spiralothelphusa hydrodroma*, a significant food source in South India, leading to a reduction in essential nutrients such as proteins, carbohydrates, and lipids. Additionally, in *Catla*, exposure to dye effluent strongly affected the feeding rate, absorption efficiency, and food conversion (Sekar *et al*., 2009).

The discharge of textile dyes into aquatic ecosystems poses serious environmental and health risks due to their low biodegradability and chemical stability. These dyes block light penetration, disrupting photosynthesis and destabilizing the delicate balance of aquatic ecosystems. Such pollution affects water quality by changing its color and odor, leading to health issues like allergies, skin irritation, and even cancer. Around 60-70% of azo dyes, commonly used in textiles, are toxic and resistant to conventional treatments, causing bioaccumulation and persistent environmental damage. High levels of organic and inorganic pollutants increase biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total organic carbon (TOC) in water, impeding treatment processes. Synthetic dyes, with their stable aromatic compounds, resist natural degradation and accumulate in the food chain, threatening both aquatic species and humans with toxic concentrations. Chlorine-based disinfection can form harmful trihalomethanes (THMs), linked to cancers and immune issues. Azo dyes, especially the diazo and cationic types, are among the most hazardous due to their carcinogenic potential. Addressing these impacts demands more effective wastewater treatments to reduce the severe environmental and health risks posed by textile dye pollution.

**2. Impact on Algae:** The increasing concentration of dyes in water bodies affects various parameters of algae, including growth, protein content, pigment levels, and other nutrients. Different dyes exert different effects on algae, with algae being 50% more sensitive to contaminants compared to organisms typically used in toxicological tests. (Klaine *et al*., 1995). In *Spirulina platensis*, higher dye concentrations led to inhibited growth and reduced nutrient levels. The dye *Ramazol Red Brilliant* also disrupted the aquatic environment, causing ecological imbalances. Furthermore, the use of indigo dye significantly reduced the growth and biomass production of the freshwater microalga *S. quadricauda*, while also altering its morphological characteristics (Dwevedi S, 2013).




Source: Al-Tohamy *et. al* (2022)

## Conclusion

The increasing presence of synthetic organic dyes in aquatic ecosystems poses a significant environmental concern. Due to their stability and resistance to biodegradation, these dyes persist in water bodies for extended periods, contributing to widespread ecological damage. Synthetic dyes effluents have adverse effects on various aquatic organisms, including fish, crabs, and algae. The textile industry is a major contributor to water pollution due to its extensive use of synthetic dyes. The large volumes of dye-laden wastewater produced annually, coupled with the challenges in effectively removing these pollutants, highlight the need for more efficient wastewater treatment solutions and stronger environmental regulations. Ongoing research and monitoring are essential to fully understand the impact of textile dye pollution on both aquatic ecosystems and human health. To mitigate these issues, the industry must adopt more sustainable practices, and collective efforts should focus on reducing the environmental consequences of dye discharge into water bodies.

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