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## REVIEW ARTICLE

# Textile Industry Pollution: Environmental Impact and Health Consequences

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**ABSTRACT**
*The textile industry significantly impacts the global economy, generating vast volumes of effluent that surpass global discharge limits. These pollutants alter environmental components' natural composition, posing substantial environmental and health risks. Textile wastewater, a by-product of dyeing, finishing, and treatment operations, contains harmful substances like dyes, surfactants, heavy metals, inorganic salts, organic contaminants, oil, and grease. Untreated or inadequately treated textile effluents discharged into water bodies disrupt aquatic plant biology and photosynthesis, degrading aquatic ecosystems and affecting waterways. This result in decreased biodiversity, altered species composition, and disrupted aquatic food webs. The prolonged presence of dyes, their sediment accumulation, breakdown into carcinogenic or mutagenic compounds, and low aerobic biodegradability exacerbate aquatic pollution. Freshwater contamination jeopardizes drinking water quality, posing significant health risks to local residents. Soil contamination occurs when textile wastewater leaches into the ground, damaging soil health and fertility. Volatile organic compounds (VOCs) from textile manufacturing contribute to air pollution, increasing respiratory issues and health concerns in nearby communities. The cumulative impacts of textile wastewater on human health, water, air, soil, crops, and plants underscore the urgent need for sustainable practices and effective wastewater treatment techniques in the textile sector. This systematic review investigated the association between textile industry pollutants and their environmental and health impacts. The findings unequivocally confirm that textile industry pollution has severe and far-reaching detrimental effects on both the overall environment and human health. The study highlights the interdependence of textile wastewater problems, emphasizing the necessity for a comprehensive strategy to address this critical issue.*
***KEYWORDS**: Textile wastewater, Environmental pollution, Human health risks, Heavy metals, dyes*

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## INTRODUCTION

Water pollution, driven by overpopulation, urbanization, industrial growth, and wastewater generation, has become a pressing environmental concern. The textile industry, a significant sector in many nations, including India, Sri Lanka, Pakistan, and China, generates substantial volumes of wastewater daily [1]. The textile sector consumes enormous amounts of water, with average-sized mills utilizing approximately 200 liters per kilogram of cloth produced daily [2]. According to the World Bank, 17-20% of industrial wastewater originates from textile dyeing and finishing processes. Synthetic dyes, with complex molecular structures, are extensively used, reaching production levels of nearly $7 \times 10^7$ tons [3]. Untreated textile wastewater is frequently discharged into lakes and rivers, contaminating water supplies and agricultural land (Figure 1). This effluent contains chemicals like acids, alkalis, colors, hydrogen peroxide, starch, surfactants, dispersion agents, and metal soaps (Table 1). This polluted water reduces soil productivity, impacts crop yields, and harms aquatic life [1]. Artificial dyes impair plant photosynthesis and aquatic life due to delayed re-oxygenation [4]. Heavy metals, such as Hg, Pb, Zn, As, Cd, Cr, Co, Cu, Fe, and Al, pose health concerns[5].The presence of heavy metals and coloring chemicals slows microbial activity, causing biological treatment systems to fail [6]. Improper disposal of industrial waste contaminates water, air, and soil, threatening human well-being [7]. Effective industrial waste management is crucial for sustainable growth. Ensuring consistent raw material supply and effective waste disposal are vital for manufacturing sectors. Therefore, acquiring practical knowledge and developing strategies for treating textile wastewater is essential to protect the environment. This comprehensive review examines the sources and consequences of textile pollution on the environment and human health.

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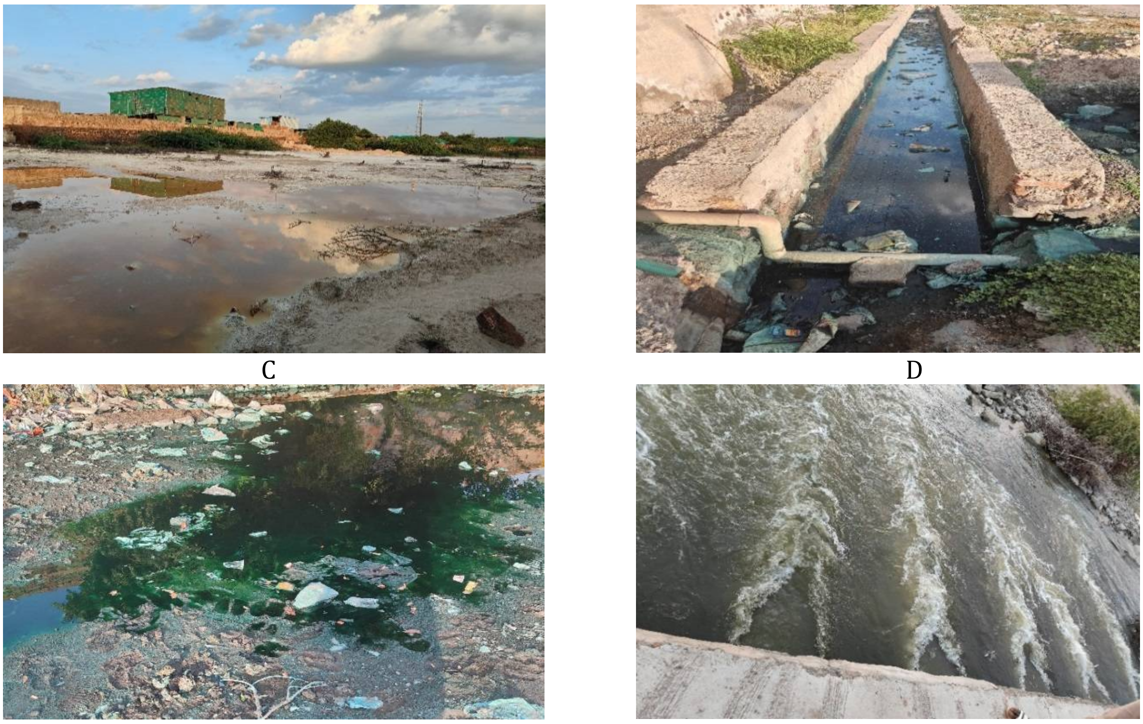

**Figure 1: A) Effluent released from the textile industry (Balotara, Barmer) accumulated in nearby land B) textile wastewater gathered in the drainage C) textile effluent spread along the area behind the city road D) The river(luni)contaminated bytextile wastewater.**

## MATERIAL AND METHODS

A systematic literature search was conducted using keywords such as "textile industries," "heavy metals," "dyes," "polluted water," and "health impact" across multiple databases, including Scopus, Cochrane, Web of Science, Google Scholar, and PubMed. A thorough review of literature published between 2018 and July 2024 was undertaken to gather data for this study. The search strategy encompassed various environmental components and health impacts associated with textile pollution.

**Table 1: Parameters and chemical compositions of textile wastewater**

| S.No. | Parameters | Content | References |
|---|---|---|---|
| **1.** | Main textile components | dyes, pigments, salts, metals, biocides, acids, alkalis, salts, dispersants, binders, humectants, hydrogen peroxide, surfactants, detergents, dioxin, chlorinated solvents reducing agents, oxygenated solvents, organic and inorganic components. | [8] |
| **2.** | Acids | Acetic and Sulphuric acid | [9] |
| **3.** | Bases | Sodium hydroxide, Sodium carbonate | [10] |
| **4.** | Salts | Sodium chloride, Sodium sulphate | [11] |
| **5.** | chlorinated solvents | carbon tetrachloride ($CCl_4$), chloroform ($CHCl_3$), methylene chloride or dichloromethane ($CH_2Cl_2$), tetrachloroethylene ($C_2Cl_4$), trichloroethane ($C_2H_3Cl_3$), and trichloroethylene ($C_2HCl_3$) | [8, 12] |

 

| | | | |
|---|---|---|---|
| **6.** | organic components | Aliphatic hydrocarbons (cyclohexene ($C_6H_{10}$), cyclohexane ($C_6H_{12}$), n-hexane ($C_6H_{14}$), n-heptane ($C_7H_{16}$), pentane ($C_5H_{12}$), and petroleum ether) and aromatic hydrocarbons (benzene ($C_6H_6$), naphthalene ($C_{10}H_8$), toluene ($C_7H_8$), and xylenes or dimethylbenzene ($C_8H_{10}$) | [13] |
| **7.** | oxygenated solvents | methanol ($CH_3OH$), ethanol ($C_2H_5OH$), propanol ($C_3H_7OH$), butanol ($C_4H_9OH$), ethylene glycol ($C_2H_6O_2$), diethyl ether (($(C_2H_5)_2O$), ethyl acetate ($C_4H_8O_2$), acetone ($C_3H_6O$), methyl ethyl ketone or butanone ($C_4H_8O$), methyl isobutyl ketone ($C_6H_{12}O$), and methyl n-butyl ketone or 2-hexanone ($C_6H_{12}O$) | [14] |
| **8.** | Heavy Metals | Zn, Cd, Pb, Hg, Cr, As, Fe, Co, Al, and Cu | [5] |
| **9.** | Textile Dyes | Coomassie Brilliant Blue G-250 (acid blue 90), Indigo Carmine (acid blue 74), Remazol Brilliant Blue R (Reactive Blue 19), Acid Fuchsin, Alizarin, Congo Red, Crystal Violet, Methyl Orange, Malachite Green, Methylene Blue, Rhodamine 6G, Auramine O, Eosin Y, Orange-II etc. | [15, 16] |
| **10.** | Biocides | chlorothalonil, diuron or dichlofluanid | [17] |
| **11.** | Surfactants | Anionic surfactants (carboxylates, better known as soaps (alkali metal salts of fatty acids), sulfonates, sulphates and phosphates) and Non-ionic surfactants | [18, 19] |
| **12.** | Reducing agents | Sodium hydrosulphite, Sodium sulphide | [20] |
| 13. | Stabilizer | Sodium Silicate, Sodium Nitrate, Organic Stabilizer | [21] |

**IMPACT OF TEXTILE WASTEWATER ON ENVIRONMENT**

Textile wastewaters produced at various phases of textile manufacturing include large levels of contaminants that, if discharged without proper treatment, are very detrimental to the environment. Wastewater may contaminate groundwater, surface water, air,soil, and aquatic system(Figure 2). Textile industry wastewater (TIWW) contains high concentrations of hazardous chemical pollutants, including acids, alkalis, salts, dispersants, binders, humectants, dyestuffs, hydrogen peroxide, surfactants, detergents, dioxin, and reducing agents.The textile sector utilizes a wide range of toxic substances, such as sizing, anticreasing, sequestering, whitening, softening, and finishing agents, which are then released into the environment[22].Textile dyes, employed as coloring agents due to their strong resistance to chemicals, light, detergents, and microbiological action, pose significant environmental risks. Even at low concentrations, dyes can seriously harm the environment, causing macro- and microorganism deaths, reducing dissolved oxygen (DO) levels, and potentially leading to anaerobic ecosystems, hydrogen sulfide production, and acidification [23].Non-biodegradable heavy metals in TIWW accumulate in living cells through the food chain, posing detrimental effects on organisms.These metals can enter the food chain, causing severe health risks, including diarrhea, liver disease, neuromuscular disorders, bleeding, dermatitis, central nervous system disorders, and renal malfunctions [24].Furthermore, the effects of TIWW on live cells are well-reported to be toxic, carcinogenic, mutagenic, and cytotoxic, highlighting the urgent need for effective textile wastewater management to mitigate harm to ecosystems and human health.

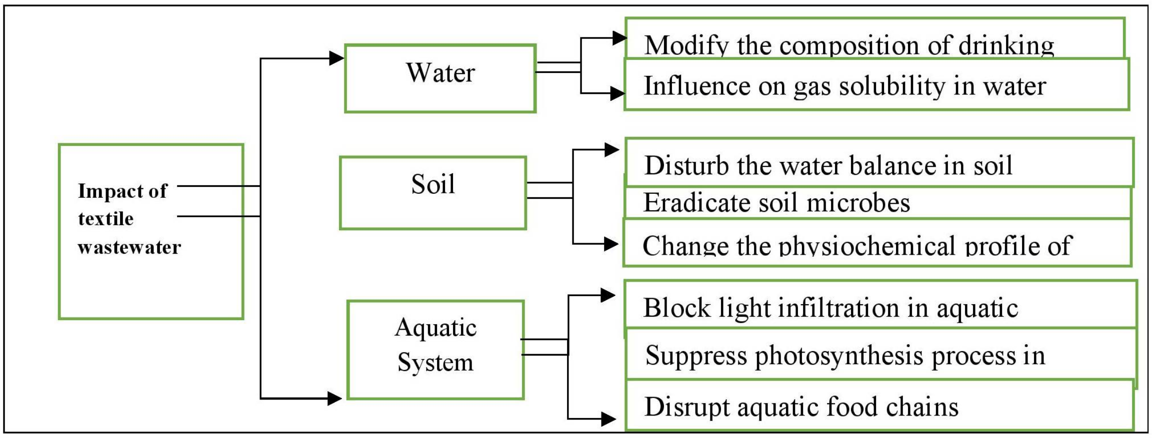


**Figure2: Flowchart showing impact of textile wastewater**

 

**Impact on Aquatic Ecosystem**

Textile effluent colors harm aquatic life and plant photosynthesis due to reduced light penetration and oxygen consumption. This decrease in photosynthesis impacts producers, affecting the entire aquatic food chain. Textile dye effluents target a variety of aquatic species (Table 2). These compounds affect growth, behavior, and oxidative stress in such organisms [25]. The altered interaction between prey and predator leads to species extinction, causing an uneven increase in remaining species.Textile effluent toxicity, attributed to component metals and chlorine, harms marine life. Suspended particles choke fish gills, while decreased algae productivity reduces food and oxygen production. Textile dyes also interfere with municipal wastewater treatment processes, such as UV decontamination [26]. The textile industry's hydrosulfide-group compounds obstruct light, disrupting chemical and biological oxygen demand (COD and BOD) levels. Chromium in textile dyes causes oxidative stress, damaging plant growth, photosynthesis, and CO2 absorption [27]. Effluent discharge into water systems disrupts aquatic life's osmoregulatory system, rendering water unfit for its original purpose.

**Table2: Various dye impact on aquatic system**

| S. No. | Synthetic dye name | Impact on aquatic life | References |
|---|---|---|---|
| 1. | Ionic dyes<br>ex: - Methylene blue | Harmful to invertebrates, fish and other aquatic organisms.<br>It suppresses certain protein content, growth rate, and chlorophyll pigment. As a result, photosynthetic rates decline in *Spirulina platensis and Chlorella vulgaris*. | [28, 29] |
| 2. | Non-ionic disperse dye<br>Ex: - Disperse blue 56 | Negative impact on hydrophytes | [30] |
| 3. | Non-ionic vat dye<br>ex: - Indigo dye | Restricted influence impact on aquatic biodiversity.<br>Negative effects on the cell density, growth rate, dry weight, biomass output, chlorophyll a, and coenobium size in Scenedesmusquadricauda ABU12. | [31] |
| 4. | Anionic acid dye<br>ex: - Congo red | Detrimental effects on invertebrates, and fish. In photosynthetic organisms, it influences growth and metabolic processes. | [32] |
| 5. | Anionic direct dye<br>ex: - Lanasyn olive<br>Lanasyn brown | Toxic to aquatic invertebrates.<br>Growth rate, pigments involved in photosynthetic reactions, protein synthesis, and concentrations of critical components including C, N, H, and S all declined. *Spirulina platensis* was shown to exhibit severe metabolic disruption in algal populations. | [33] |
| 6. | Anionic reactive dye<br>ex: - Reactive orange 16<br>Remazol Brilliant Blue | Harmful impact on aquatic vegetation.<br>The algal species *Selenastrum capricornutum* (microalga) was the susceptible species to determine the toxicity of the dyes.<br>Disrupt the tropic level of the food chain and finally upsetting the ecological equilibrium in *Chlorella vulgaris*. | [34] |
| 7. | Cationic dyes<br>ex: - Malachite green | Potential toxicity to fish and aquatic flora.<br>It modifies protein profiles and raises ROS levels in *Chlorella* and *Daphnia*, respectively, causing morphological and cellular alterations as well as inducing genetic damage. | [35] |

**Impact on fish biota:**

Textile effluent has been shown to have detrimental effects on freshwater life. Fish exhibit high responsiveness and sensitivity to alterations in their aquatic environment, with any adverse changes reflected in their biochemical, histological, and physiological traits.The toxic impacts of textile effluents present a direct and indirect threat to fish biota owing to the direct accumulation of pollutants and the rise in physical features such as color, turbidity, temperature, and total solids, which disrupt the fish food chain. Several experiments have demonstrated that dyes also contribute to the permanent structural modification of fish DNA, which happens even at hazardous levels that are otherwise healthy for life [36]. A comparative toxicological examination of *Gambusia affinis* revealed cytotoxic effects on red blood cells and significant reductions in mortality, accompanied by a decline in cell quantity and alterations in size and structure [37]. Similarly, *Mastacembelus armatus* exposed to textile effluent experienced changes in ion control in kidneys, liver, and muscles, altering sodium, chloride, potassium, calcium, and magnesium ion concentrations [38].The textile industry's wastewater also causes aberrant behaviour in Teleost fish, such as *Poecilia recticula*, including hyperexcitation, rapid breathing, and histopathological changes, as well as intestinal damage and hemoglobin entering the lumen [39]. Studies on *Mossambicus oreochromis* revealed notable histological alterations in the liver, including hyperaemia, necrosis, and degeneration, using specific hematological parameters[40].Similarly, *Catla* experienced significant impacts on feed absorption and food conversion rates from dye effluent [41].Acute and chronic exposure experiments on *Labeo rohita* in polluted rivers revealed significant protein decreases and accumulation of glycogen and lipids due to high heavy metal concentrations[42]. Additionally, a study in Nigeria found textile factory wastewater to be highly toxic, causing signs of toxicosis, loss of balance, irregular swimming, weakness, and death in juvenile *Oreochromis niloticus*, with the influent being 6.58 times more hazardous than the effluent [43].

**Impact on algae biota:** Algae grow swiftly and readily, and they are very sensitive to chemical stress. The increased use of dyes in water bodies significantly impacts algae, affecting their pigment content, protein levels, and overall nutritional value[44]. Algae respond differently to various dyes, and excessive dye concentrations in textile industry wastewater can prevent light penetration, inhibiting or halting algal cell growth [45].Algae are more sensitive to toxins than species commonly used in toxicological tests, making them a reliable indicator of aquatic ecosystem contamination[46]. High dye concentrations in water reduce its nutritional value and hinder the growth of *Spirulina platensis*[47].Microalgae are used to monitor water quality and identify environmental issues. Recent research has employed microalgae to assess the toxicity of several substances, including metals, herbicides, and insecticides in addition to dyes[36]. Specific dyes, such as Ramazol Red Brilliant and Indigo, can have devastating effects on aquatic ecosystems. Chlorophyll A production, cell density, and dry weight production have all been observed to be adversely influenced by the high proportion of indigo dye wastewater [36].

**Impacton aquatic food chain:** Water contamination typically results from an abundance of non-biodegradable organic molecules, particularly colors and their derivatives from textile dyeing. Textile dyes can contaminate aquatic habitats, harm aquatic life, and induce oxidative stress in aquatic organisms [25]. The color generated during dyeing obstructs sunlight, reducing photosynthesis and depleting oxygen in water, affecting aquatic plants and animals. The lack of algae and inherent toxicity of dyes contribute to aquatic life suffering in affected areas. Textile dyes have carcinogenic, mutagenic, and toxic propertiesand can biomagnify in food chains [48]. As these xenobiotics accumulate in fatty tissues of aquatic and terrestrial creatures, they enter the food chain through ingestion [46]. Algae, primary producers in aquatic ecosystems, are sensitive to water quality changes, impacting ecosystem equilibrium. Fish, occupying various trophic levels, are bioindicators of water pollution and can transfer contaminants to humans through the food chain. Consequently, animals at higher trophic levels are more contaminated than those at lower levels, highlighting the significance of addressing textile dye-related water pollution.All worldwide environmental compartments, including aquatic environments, have detected microplastics as ubiquitous contaminants. The ingestion and trophic transmission of microplastics among aquatic organisms have been extensively documented. A multitude of research has shown that microplastics may be transmitted via higher-trophic-level food webs, posing risks of accumulation and toxicity [49].

**Impact on Air**

Textiles offer various benefits, including softness and sound absorption, but their processing and treatment can negatively impact indoor air quality due to chemical usage. Air pollution is the second most significant kind of pollution in the textile sector[50].Air pollution is measured by the amount of carbon dioxide, carbon monoxide, and other metal-related gases produced; $SO_x$ and $NO_x$ are also contributing to air pollution [51].Key sources of air pollution in the textile industry includes textile processing activities, such as printing, dyeing, fabric preparation, resin finishing, and drying, release harmful substances. High-temperature drying and curing processes emit hydrocarbons from mineral oils and drying ovens. Additionally, volatile substances like formaldehydes, acids, and softeners are released during these operations. The textile industry's wet processing procedures, particularly dyeing and printing, generate gaseous emissions, including sulfur, carbon monoxide, carbon dioxide, and carbon, contributing to air pollution. Air pollution from textile operations poses significant respiratory risks to humans and animals.The oxidation of NO, which produces $NO_2$ at elevated temperatures from atmospheric nitrogen and oxygen, serves as its primary source. NOx is an important precursor to ozone and particulate matter.It may promote the formation of photochemical smog, reduce visibility, cause acid rain, and contribute to ozone depletion. These compounds, mostly composed of $NO_x$, NO, and $NO_2$, significantly harmed people by infiltrating the alveoli and bronchioles in the deepest regions of the respiratory system, and in extreme instances, they resulted in premature mortality. Furthermore, due to its role in the formation of acid rain and nitric acid, $NO_2$ is detrimental to ecosystems. The global textile industry introduces over 100 million metric tons of new goods annually [51]. The considerable quantity of textile production serves as a poignant indicator of the textile industry's profound and far-reaching environmental consequences. The textile industry is often condemned for its adverse environmental impact due to the extensive use of hazardous chemicals and the emission of toxic air pollutants, including $SO_2$ and $NO_X$[50].

**Impact on Water**

The textile industry is well-known for water contamination because of its high-water consumption and the release of coloring chemicals into wastewater. Industrial dye effluent primarily harms receiving water bodies, such as lakes, rivers, and oceans, and has far-reaching consequences for other living organisms. This wastewater pollutes the water surface, rendering it unsafe for irrigation. Textile dyeing operations generate significant organic matter and color-producing compounds, contaminating water with high biological oxygen demand (BOD), chemical oxygen demand (COD), color, and pH levels[52]. Untreated textile effluent can deplete dissolved oxygen in surface water bodies due to its high BOD content, poisoning biological life with elevated COD levels. Moreover, textile wastewater obstructs oxygen transfer mechanisms, preventing water self-purification. The presence of heavy metals in textile effluent contaminates water supplies, posing serious health risks to humans and animals, including cancer, skin conditions, liver and kidney damage, and cognitive decline[53]. Wastewater discharge into drains and rivers also corrodes sewage pipes, renders drinking water unsuitable for consumption, and causes maintenance issues. Although water pollution may not always be visible, its effects persist in fish and sediments, making contamination assessment challenging. The aesthetic impact of colored watercourses often overshadows the environmental risks, with "non-natural" colors sparking greater concern. Water recycling and reuse via wastewater treatment are effective options for conserving and increasing current water supplies while reducing harmful pollutant discharge into the environment.

**Impact on Soil**

Soil plays a vital role in the life cycle and serves as a fundamental source for agricultural growth. Textile effluents are disposed of on bare ground, and improper disposal leads to serious soil pollution. Irrigating agricultural fields with industrial wastewaters can significantly alter soil physicochemical characteristics, such as pH, temperature, organic matter, electrical conductivity, and hydraulic properties. This alteration occurs due to pore clogging and soil texture stiffening, which hinders root penetration. Textile effluents, for instance, contain high levels of heavy metals like zinc, copper, and chromium, posing ecological risks to plants and soil. Furthermore, industrial effluents can impact soil physical, chemical, and fertility properties by influencing microorganism activity and diversity in agricultural fields.

**Figure 2: Textile effluent contaminated nearby land**

 

**Impact on pH value and electrical conductivity of soil**

Irrigation with wastewater can alter soil pH, typically decreasing it due to cation oxidation [54]. This decrease in pH increases heavy metal solubility, making them more bioavailable for plant. Soil pH also influences metal adsorption, with lower pH values promoting anion exchange capacity and higher pH values enhancing cation exchange capacity [55]. Wastewater irrigation additionally increases soil electrical conductivity (EC) compared to groundwater irrigation, leading to heightened soil salinity and reduced crop yields, such as tomato output [56]. Studies in textile industrial areas have confirmed these findings. In Pali, soil pH ranged from 7.28 to 9.25, indicating alkaline soil with a mean pH of 8.15, exceeding standard values [57]. Elevated EC values (1.03-1.82 μs/cm) were attributed to increased chemical salts from textile industries, rendering the soil unsuitable for plant growth. Similarly, in Jaipur's Sanganer Industrial Area, soil pH ranged from 7.72 to 9.6, suggesting alkaline effluent discharge from textile factories [58]. The presence of ionic matter in industrial effluent increased soil conductivity, indicating heightened cation and anion availability [59].

**Impact on soil organic content**

Organic matter is crucial for maintaining soil productivity. Wastewater irrigation can enhance soil fertility by increasing organic matter content. Soil organic matter consists of humic and non-humic substances, with fulvic and humic acids being key components of humus [60]. Humic acids, high molecular weight organic acids, are insoluble at lower pH values and precipitate out of soil solutions. In contrast, fulvic acids, low molecular weight organic acids, have more active sites and remain soluble across all pH values [60]. Studies have shown mixed effects of textile effluents on soil health. Short-term experiments have found increased water-soluble salts, organic matter, and nutrient levels (Na, Ca, Mg, K, NH4-N, and P) in soil irrigated with textile effluents compared to regular water [61]. However, long-term exposure can harm soil health. For instance, a study in the Pali textile industrial area found substandard organic carbon levels (0.25-0.41%) indicating unproductive soil, hindering plant nutrient uptake [57]. This highlights the need for organic manure application to improve soil fertility.

**Impact on soil temperature**

Soil temperature significantly impacts metal accessibility and mobility, as well as soil microorganism health, which regulates soil fertility. Wastewater irrigation can increase soil temperature due to enhanced organic matter breakdown, making metals more available. Elevated temperatures facilitate zinc and copper transfer from soil to plants. Studies have observed this phenomenon in industrial areas. For instance, Malik [58] reported higher soil temperatures (18-20°C) at Jaipur's Sanganer Industrial Area, compared to forest soil (17-18°C), likely due to chemical reactions in textile wastewater.

**Impact on redox potential,bulk density and porosity**

The mobility of metals in soil solutions depends on their redox state, which determines their ability to accept or donate electrons. This redox potential influences the availability and movement of metals, whether they exist in reduced or oxidized forms [54].Soil bulk density, expressed as $g/cm^3$, represents the mass of undisturbed soil per unit volume. Due to pore space, soil bulk density is always lower than particle density. As bulk density increases, soil porosity decreases. Long-term wastewater irrigation alters soil bulk density and porosity, influenced by wastewater quality, specifically dissolved and particulate element concentrations. For instance, effluents from the North Bengal Sugar Mill in Bangladesh decreased soil bulk density from 1.44 to 1.42 $g/cm^3$ and increased porosity by 2.17% [62]. Conversely, high organic carbon levels near industries, such as in Jaipur's Sanganer Industrial Area, indicate accumulated organic waste. This can degrade soil quality by reducing bulk density (1.09-1.30 $g/cm^3$) compared to forest soil (1.39-1.73 $g/cm^3$) [58].

**Impact on hydraulic conductivity and infiltration rate**

Irrigation with wastewater significantly alters soil hydraulic conductivity and infiltration rates[63]. These variations are influenced by several factors, including soil type, clay content, $CaCO_3$ concentration, soil humidity, and wastewater characteristics[64].The duration of wastewater irrigation also plays a crucial role. Research has shown that prolonged irrigation (up to 15 years) can lead to increased infiltration rates due to the emergence of wide fissures in the soil. Conversely, shorter-term irrigation (up to 5 years) drastically reduces infiltration rates [65].

**Impact on Crops and Plants**

Wastewater irrigation for vegetable growing raises concerns regarding the presence of hazardous metals in irrigated soil and produce, which may endanger human health.Textile wastewater's release of heavy metals significantly impacts plant growth, leading to decreased microbial diversity and activity, reduced seed germination, and stunted seedling growth. Due to hazardous materials, untreated textile wastewater is unsuitable for irrigation.The negative impacts of textile wastewater irrigation methods on crop production and soil nutrient levels are mostly caused by the deposition of resistant azo dyes in the soil[66]. Undiluted textile wastewater can hinder plant growth [67], but dilution can have beneficial effects[68]. Studies have shown that diluting wastewater boosts germination and development in crops like black gram, green gram, rice, peanut, sunflower, and maize[67]. Specifically, a 25% dilution of textile effluent can be used for irrigation[69]. Textile wastewater application to rice seedlings increased lead, zinc, iron, manganese, and copper concentrations significantly compared to high-quality irrigation water. Industrial pollution's impact on plants varies with distance from emitters, with wheat plants grown closer to pollution sources exhibiting reduced yields and growth rates, as well as biochemical disorders [70]. Metal uptake by plants depends on factors like plant type and age, soil type, pH, and organic matter content. Plant species differ in heavy metal elimination and retention abilities. Metals accumulate in plant roots or are translocated to shoots, with variations between plants. For example, lead deposits mainly in roots, while copper and zinc accumulate in both roots and shoots [71].Recent studies have highlighted concerns about textile effluent's impact on crops. Begum *et al*., [72] found elevated nitrogen concentrations in textile effluent harmed jute vegetable yields in Bangladesh. Hassan *et al*., [70] revealed heavy metal accumulation in edible crops irrigated with textile dyeing effluent, posing health risks, particularly for Indian spinach consumption. The majority of research has indicated that irrigating plants with partly diluted effluents improves the development and growth of other plant morphological features. In contrast, extremely concentrated textile effluent had a deleterious effect on plants[73]. Research has consistently shown that textile industry effluents can significantly impact seed germination. Elevated pressure and high osmotic pressure from textiles, paper, marble, dairy, and breweries reduce seed germination[36]. Exposing bean and ladyfinger plant species to industrial effluents decreased seed germination, whereas treated wastewater posed no threat. In contrast, untreated textile wastewater significantly reduced germination and early growth of radish, turnips, and brassica, with turnips showing the most noticeable impact[74].Yousaf *et al*., [75] discovered that lower concentrations of sewage promoted seed germination and growth, but higher concentrations gradually reduced these parameters[76]. Optimal seed germination and growth occurred at a 25% concentration of textile wastewater, indicating safe use for irrigation with sufficient treatment and dilution.Raia &Khan [77] examined the impact of industrial effluents containing Fe, Cu, Zn, and Mn on barley seed germination and growth, highlighting pollutant accumulation in edible plant portions and negative effects on consumers. Muhammad *et al*., [74] observed decreased germination of mung bean and okra seeds at concentrated textile wastewater levels (75–100%), but no effects at concentrations up to 50%[78].While textile wastewater can improve seedling length in various crops, excessive heavy metal concentrations hinder plant development, metabolic functions, and nutrient absorption[79]. Rahman *et al*., [68] found that loom-dye effluent increased heavy metal buildup in rice seedlings compared to freshwater treatment. The order of heavy metal accumulation in crops is Fe, Mn, Pb, Zn, and Cr, with varying effluent concentrations affecting tissue function and metal absorption.

**IMPACT OF TEXTILE WASTEWATER ON HUMAN HEALTH**

Textile dyes are poisonous, carcinogenic, mutagenic, and allergenic, posing severe health risks. Textile dyes, the byproduct of cytochrome family enzymes, are consumed by humans via food chains and contaminated water. These colors form DNA and protein adducts, which result in free radicals, oxidative stress, and apoptotic cascades. They also have an effect on epigenetic processes, like DNA methyltransferase and histone deacetylase which may promote cancer and cause harm to many organ systems [25]. Health risks associated with dyes include eye irritation, high blood pressure, fever, rapid heartbeat, mental illness, nausea, jaundice, cyanosis, and tissue necrosis [80]. In the textile industry, byssinosis, a respiratory illness caused by inhaling cotton, flax, or hemp dust, is a major health concern. Additionally, noise levels from machinery can exceed regulatory limits, causing hearing impairment [81]. The use of dyes and pigments can harm health, affecting workers immediately and consumers later in the product's life cycle. Prolonged skin contact with clothing contaminated with toxic substances can lead to absorption, accumulating heavy metals in vital organs like the liver, kidney, bones, heart, and brain [82]. Children are particularly vulnerable to developmental and quality-of-life impacts from exposure to poisonous dyes and heavy metals. Water-soluble azo dyes become hazardous when degraded by liver enzymes and can be easily absorbed through skin and mouth when individuals come into contact with wastewater [83]. This is particularly concerning for villagers who irrigate fields with toxic wastewater, leading to symptoms like tooth plaque, knee pain, and premature greying. Synthetic dyes, widely used in various industries, pose significant health risks due to their carcinogenic, mutagenic, and genotoxic properties (Table 3). Azo dyes, commonly used in textiles, food, cosmetics, paper printing, leather, textile, paint, and pharmaceutical sectors, are particularly hazardous. Notorious azo dyes include Direct Black 38, azodisalicylate, 2-nitroaniline, 4-chloroaniline, and benzidine derivatives, linked to cancer in humans and animals. Exposure to these dyes can induce DNA damage, chemosis, exophthalmos, vomiting, severe tubular necrosis, lacrimation, hypertension, vertigo, and lifetime blindness. Specific dyes, such as Amido black 10B [84], Methyl orange[85], Eriochrome Black T, and Rhodamine B[86], exhibit neurotoxic, carcinogenic, and genotoxic properties. Other hazardous dyes include Basic Red 9, which has been linked to cancer and breaks down into carcinogenic aromatic amines [87]. Triphenylmethane dyes, such as Brilliant Green, Crystal Violet, and Malachite Green, also act as carcinogens and mutagens, posing risks to humans and aquatic life[88]. Additionally, Sudan I convert to aromatic amines that cause cancer, while Methylene Blue has potential side effects including elevated blood pressure and cardiac depression [89]. Furthermore, Azure B interacts with DNA and RNA and inhibits human glutathione reductase, exhibiting harmful effects[90]. Prolonged exposure to these dyes on workers has been linked to bladder cancer, splenic sarcoma, and hepatic carcinoma [91].

**Table 3: Impact of dyes on human health**

| S.No. | Class | Dye Name | Molecular Formula | Impact |
|---|---|---|---|---|
| 1. . | Azo | Amido Black 10B | $C_{22}H_{14}N_6Na_2O_9S_2$ | Respiratory tract damage, breathing difficulties, shortness of breath, burning, and red, painful rashes [84]. DNA damage (both Comet assay and MN test) in human-origin cells [92]. |
| | | Eriochrome Black T (EBT) | $C_{20}H_{12}N_3O_7SNa$ | Carcinogenic and poisonous anionic azo dye [86]. |
| | | Disperse Red 1 | $C_{16}H_{18}N_4O_3$ | Increases the frequency of micronuclei in hepatocyte imitative cells, human lymphocytes, and human hepatoma (HepG2) cell lines in vivo [93]. |
| | | Met anil yellow | $C_{18}H_{14}N_3NaO_3S$ | Toxic hemoglobinemia and very harmful carcinogen [94]. |
| | | Methyl orange | $C_{14}H_{14}N_3NaO_3S$ | Short-term and long-term impacts on aquatic life [85]. |
| | | Rhodamine B | $C_{28}H_{31}CIN_2O_3$ | Neurotoxic, carcinogenic, and genotoxic to humans and animals. Causes irritation to the skin, eyes, and respiratory tract [95]. |
| | | Sudan I dye (Solvent Yellow 14) | $C_{16}H_{12}N_2O$ | Cause cancer and Liver nodules [96]. |
| | | C.I. Basic red 18 | $C_{19}H_{25}CI_2N_5O_2$ | Mutagenic effects on Ames Salmonella typhimurium strains causing frame shift mutations [97]. |
| | | Reactive red 120 | $C_{44}CI_2H_{24}N_{14}Na_6O_{20}S_6$ | Toxicity to Allium cepa indicates harmful effects on the root cells [98]. |
| | | Reactive Dyes Red 3BS | $C_{31}H_{19}CIN_7O_{19}S_6$ | Liver and gill tissues of *Oreochromis niloticus* displayed diverse anti-oxidant activities of catalase (CAT) and glutathione reductase (GR) and glutathione s-transferase (GST), and histopathological changes [99]. |
| | | Solvent Yellow 56 | $C_{16}H_{19}N_3$ | An estrogenic compound with reduced efficiency [100]. |
| | | Disperse Orange 1 | $C_{18}H_{14}N_4O_2$ | Micronuclei is increased in human lymphocytes and HepG2 cells [97] |
| | | Astrazon Blue FGRL | $C_{20}H_{26}N_4O_6S_2$ /$C_{21}H_{27}ClN_4O_3S$ | Glutathione reductase (GR) and glutathione s -transferase (GST) levels have risen in *Xenopus laevis* tadpoles [101]. |
| | | Astrazon Red FBL | $C_{18}H_{21}BrN_6$ | Notable decline in levels of *Phanerochaete chrysosporium*, catalase, glutathione reductase, glutathione s-transferase, and glutathione with elevated functions in Carboxylesterase (CaE), Lactate dehydrogenase (LDH), and glutathione s-transferase (GST) in Xenopus leaves [101]. |
| | | Remazol Red R R | $C_{31}H_{19}ClN_7Na_5O_{19}S_6$ | At minimum concentration, there is a considerable spike of glutathione s-transferase (GST) operation, and increase in carboxylesterase (CaE) activity [101]. |

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|---|---|---|---|---|
| | | | | considerable effect on the kidney but a slight effect on the liver in mice [102]. |
| | | Cibacron Blue FN-R | $C_{29}H_{20}ClN_7O_{11}S_3$ | Inhibitory effect on glutathione s-transferase with a rise in the activity of carboxylesterase (CaE) in *Xenopus laevis* tadpoles [101]. |
| | | Cibacron Red FN-3G | $C_{25}H_{16}ClN_7Na_4O_{18}S_6$ | Suppression of glutathione s-transferase functions in *Xenopus laevis* tadpoles at elevated concentration levels [101]. |
| | | Benzopurpurin 4B and Everzol Navy Blue FBN | $C_{34}H_{26}N_6Na_2O_6S_2$, $C_{37}H_{29}ClN_{10}O_{22}S_7Na_6$ | Effects on aquatic environment [100]. |
| | | Yellow Favina CXL | $C_{20}H_{20}ClN_9O_8S_2Na_2$ | An estrogenic compound with reduced efficiency [103]. |
| | | Direct black 38 | $C_{34}H_{25}N_9Na_2O_7S_2$ | Formation of Hepatocellular and breast in mice [104]. |
| | | Auramine O | $C_{17}H_{22}ClN_3$ | DNA damage, mutagenicity, cytotoxicity carcinogenicity, and genotoxicity.<br>enhance the metastatic capacities and stemness properties of lung carcinoma cells by the activation of aldehyde dehydrogenase family 1 member A1 (ALDH1A1). [105] |
| | | Congo Red | $C_{32}H_{22}N_6Na_2O_6S_2$ | Lethal to bacteria, protozoa algae and yeast. Induce genotoxicity, mutagenicity cytotoxicity, carcinogenicity, and microbial toxicity [106]. |
| | | Orange-II (Acid Orange 7) | $C_{16}H_{11}N_2NaO_4S$ | Mutagenicity, carcinogenicity, fish toxicity, and other environmental toxicity [107]. |
| | | Eosin Y | $C_{20}H_8Br_4O_5$ | DNA damage, mutagenicity, carcinogenicity, microbial toxicity, environmental toxicity, skin toxicity, cardiotoxicity, pulmonary toxicity, and reproductive toxicity [16]. |
| 2. | Thiazine | Azure B | $C_{15}H_{16}ClN_3S$ | Inhibitor of human glutathione reductase and related enzymes [108]. |
| | | Malachite green | $C_{23}H_{25}ClN_2$ | Elevated blood pressure, cardiac depression, the formation of Heinz bodies, cyanosis, and jaundice [89]. |
| | | Methylene blue | $C_{16}H_{18}N_3SCl$ | Mammalian cells are very susceptible to its cytotoxicity, genotoxicity, carcinogenicity, and teratogenic effects [109]. |
| 2. . | Triaryl methane | Basic Red 9 dye | $C_{19}H_{17}N_3$ | Allergic dermatitis, skin irritation, mutations, and even cancer [110]. |
| | | Acid green 16 | $C_{31}H_{33}N_2NaO_6S_2$ | Mutagenicity [112] |
| 3. . | Triphenylmethane | Brilliant green | $C_{27}H_{34}N_2O4S$ | Genotoxic, arcinogenic, and mutagenic [113] |
| | | Crystal violet | $C_{25}N_3H_{30}Cl$ | Respiratory and renal failure, irritate the skin and gastrointestinal tract, and, in extreme cases, be carcinogenic, mutagenic, and mitotically toxic [114]. |
| 4. . | Tripheno-dioxazine | Blue HFRL | $C_{41}H_{30}Cl_4N_{14}Na_4O_{14}S_4$ | Effects on aquatic environment [100] |
| 5. . | Phthalo-cyanine | Remazol Turquoise Blue G-A | $C_{18}H_{15}N_7OS$ | Enhancement of glutathione s-transferase activity in *Xenopus laevis* tadpoles [101], severely damage aquatic ecosystems [115] |
| 6. . | Anthra-quinone | Alizarin Complex | $C_{19}H_{15}N_08$ | Adverse effects associated with human serum albumin (HAS) [115] |
| | | Remazol Brilliant Blue R | $C_{22}H_{16}N_2Na_2O_{11}S_3$ | Extremely hazardous and potentially cancer-causing [116] |
| | | Disperse blue 3 | $C_{17}H_{16}N_2O_3$ | Toxicity in bacterial, protozoan and algal tests, with mutagenic outcomes in vitro by the Ames test [117] |
| | | Disperse Blue 56 | $C_{14}H_9BrN_2O_4$ | Influence on public health and aquatic ecosystem [118] |

The textile industry releases wastewater containing various toxic metals from fabric dyes, posing significant environmental and health risks (Table 4). When exposed to the human body, these heavy metals can trigger various health concerns. Heavy metals can be broadly classified into two categories: non-essential metals, including chromium, cobalt, nickel, arsenic, cadmium, and lead, and essential metals, comprising magnesium, manganese, iron, copper, and zinc[119].Prolonged exposure to these heavy metals can lead to severe health issues, including bone disorders, carcinogenicity, malignancies, kidney failure, brain damage, neurological abnormalities, gastrointestinal problems, memory impairment, and other adverse effects [120]. The implications of metal laden textile effluents on human health and fishes are further detailed in Table 4.

**Table 4: Textile heavy metals causing toxicity in humans and fishes**

| S.No. | Heavy metals | Impact on human | Impact on fish |
|---|---|---|---|
| **1.** | $Pb^{2+}$ (Lead) | Carcinogenicity, mental retardation, birth defects such as autism, brain damage, neural damage, paralysis, dyslexia allergies, kidney damage, decrease in male sperm count in men, abortions and gastrointestinal diseases, cause problems in haemoglobin (Hb) synthesis and joints [121] | Oxidative stress, behavioural changes damage the liver, kidney, spleen, and gills, immune system damage, impact fish locomotion [122, 123]. |
| **2.** | $Hg^{+}$ (Mercury) | Carcinogenicity, brain damage, gastrointestinal toxicity, liver damage, nephrotoxicity, kidney damage, skin rashes, hair loss, lung damage, neural damage, tremors, gingivitis and/or mild psychological abnormalities, spontaneous abortion, and congenital deformity, IQ scores in children[124, 125] | Disorganization of seminiferous tubules, and reduced germ cell proliferation, teratogenic effects [126] |
| **3.** | $Cd^{2+}$ (Cadmium) | bone diseases (osteomalacia, osteoporosis), pulmonary damage, skeleton damage, carcinogenicity, prostate cancer, chronic anemia, renal failure, stomach, liver, kidney, and hematological system, high blood pressure, and myocardial disease[127] | Visible external lesions such as discoloration and necrosis on livers of Cyprinus carpio, *Carassius auratus* and *Corydoras paleatus* oxidative stress, immune system damage [128] |
| **4.** | $Cr^{6+}$ (chromium) | Carcinogenic potential, hepatic impairment, and malignancies of the respiratory system (breathing problems, asthma, cough) and gastric region [129] | Damage in the liver, brain, kidney, gill, and intestine, decrease in antibody production and lymphocyte count, decrease in growth and survival rate, loss of respiratory abilities[130] |
| **5.** | $Co^{2+}$ (Cobalt) | Haematological, thyroid, hepatic, cardiovascular, endocrine, renal problems, allergic reaction [131] | DNA damage and chromosomal fragmentation, Oxidative stress, reduce reproductive success [132] |
| **6.** | $Cu^{2+}$ (Copper) | Abdominal diseases and metabolic activity irregularities [133] | External lesions in Cyprinus carpio, Carassius auratus, and *Corydoras paleatus* manifest as liver discoloration, gill edema, testicular changes, decreased egg production, reproductive complications, shorter life lengths, and lower fertility[134]. |
| **7.** | $As^{3+}$ (Arsenic) | Diabetes, hepatic and renal failure, neurological damage, malignancies, cardiovascular disorders, miscarriages, and respiratory issues[135] | Internal organs such as the kidneys, liver, and intestinal mucosa can exhibit histological abnormalities and defects, including localized hepatic necrosis, bowel proliferation, parenchymal hepatocytosis, and heart muscle apoptosis [136] |
| **8.** | $Zn^{2+}$ (Zinc) | Vomiting, diarrhea, fever, stomach cramps, and Nausea[137] | Retinal growth, respiratory and cardiac abnormalities, spawning inhibition, Skeletal deformities, dwarfism, cataracts [138, 139] |
| **9.** | $Fe^{2+}$ (Ferrous) | Dehydration, diarrhea, Vomiting, abdominal pain, and lethargy [140] | Asphyxia, respiratory disorders, neurodegeneration [141] |

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| **10.** | $Al^{3+}$ (Aluminium) | Neuronal atrophy in the locus coeruleus, substantia nigra, and striatum[142] | Disruptions to the gill and lamellar epithelium, sloughing, necrosis of the cells, death, and damage to the liver, lung, kidneys and heart [143] |
| **11.** | $Ni^{2+}$ (Nickel) | DNA damage, reduction in body weight, harm to the heart and liver, skin irritation and nasal fibrosis[144, 145] | Hypertrophy, hyperplasia, reduction of secondary lamellae, fusion of adjacent lamellae, a significant elevation in blood glucose, and pancreatic and liver disorders resulting in hyperalbuminemia, hyperproteinemia, and hypercholesterolemia, structural impairment to the gills and hepatic tissues of fish[146] |
| **12.** | $Se^{2-}$ (Selenium) | Type-2 diabetes, fatigue irritability, hair and fingernail loss, damage to kidney and liver tissue, damage to circulatory tissue, and more severe damage to nervous system[147] | Growth inhibition, decreased swimming ability, changed energy homeostasis, abnormalities in the morphological and reproductive systems, hemato-biochemical parameters, and histological alterations in key organs [148] |
| **13.** | $Sb^{3+}$ (Antimony) | Cancer, skin lesions, cardiovascular disorders, neurotoxicity, and immunological toxicity, headaches, nausea, vomiting, and diarrhea dizziness, abdominal pain, and sleep deprivation[149] | Neurotoxicity, Oxidative stress, DNA damage in Zebra fish [150, 151] |

## CONCLUSION

Textile wastewater is a complex mixture of pollutants, including dyes, chemical substances, and non-biodegradable heavy metals, which pose significant health risks. These contaminants are resistant to chemicals and light, making remediation extremely challenging. The discharge of untreated or partially treated textile effluent into water bodies has devastating consequences, reducing light and oxygen penetration, harming aquatic life, and increasing wastewater turbidity. The textile industry's wastewater also has severe impacts on soil and agriculture. Industrial wastewater alters soil properties, affects plant and soil ecology, and stimulates microbe activity, ultimately affecting soil fertility. This can lead to decreased plant development, crop production, and germination value, as well as increased accumulation of heavy metals in plants. Exposure to textile effluents can have dire consequences for human health, including eye damage, high blood pressure, mental disease, nausea, jaundice, cyanosis, tissue necrosis, and hearing impairment. Moreover, heavy metal buildup can harm children's development. The textile industry's use of poisonous, carcinogenic, mutagenic, and allergenic dyes exacerbates these health hazards.

To mitigate these impacts, immediate implementation of rules and regulations requiring management plans for treating industrial waste effluent is crucial. The textile sector must assume responsibility and adopt environmentally sustainable practices, including efficient effluent treatment facilities, eco-friendly dyes and chemicals, and modern treatment technologies. Law enforcement agencies and regulatory committees must institute rigorous laws, rules, and regulations to safeguard the environment from textile-related pollution. Ultimately, reducing the negative effects of textile wastewater on the environment and public health requires a multi-faceted approach involving government, industry, and regulatory agencies. By prioritizing sustainable practices and responsible wastewater management, we can protect biodiversity, ecosystems, and human well-being.

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