

REVIEW ARTICLE

Industrial Wastewater and Its Ecotoxicological Impact on Aquatic Life in Bangladesh: A Contemporary Review

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ABSTRACT

The rapid industrialization of Bangladesh, a cornerstone of its economic growth, has precipitated a severe water pollution crisis, posing critical threats to freshwater ecosystems. This review synthesizes current evidence on the composition, sources, and ecotoxicological consequences of industrial wastewater, highlighting major regulatory and management challenges. The textile, tannery, food processing, paper, and pharmaceutical sectors are identified as primary polluters, collectively responsible for over 97% of industrial water pollution. Their effluents consistently exceed national standards, containing alarming levels of heavy metals (e.g., Pb, Cd, Cr), organic pollutants, and elevated physicochemical parameters (BOD, COD, TDS, TSS). Geographically, hotspots include Dhaka, Chittagong, and Gazipur, where untreated discharges lead to biodiversity loss and sediment contamination. The ecotoxicological impacts are profound and multi-faceted. Heavy metals bioaccumulate, causing oxidative stress, organ damage, reproductive failure, and mortality in key fish species like *Labeo rohita* and *Oreochromis niloticus*. Organic loads and physicochemical stressors deplete oxygen, alter pH, and induce physiological stress. Emerging pollutants, particularly microplastics and PFAS, exacerbate risks by impairing organismal health and acting as vectors for other toxins. Despite regulatory frameworks like the Environmental Conservation Act (1995), effective mitigation is hampered by weak enforcement, corruption, and the high cost of treatment technologies, especially for SMEs. Many Effluent Treatment Plants (ETPs) remain non-functional or inefficient. The review concludes that safeguarding aquatic ecosystems requires an integrated strategy combining stringent regulatory enforcement, adoption of advanced and cost-effective treatment technologies, capacity building, updated standards for emerging contaminants, and targeted research. Coordinated action among government, industry, and communities is imperative to ensure the health of Bangladesh's water resources and the populations that depend on them.

Keywords: Industrial Wastewater, Ecotoxicology, Bangladesh, Heavy Metal Pollution, Aquatic Ecosystem Management

ARTICLE INFO

Received: 12 January 2025 | Accepted: 7 March 2025 | Available online: 25 June 2025

CITATION

chakma. Healthcare Waste Management in Bangladesh: A Review of Environmental and Health Impacts. *Ecological Risk and Security Research* 2025; 3(1): 12208. doi: 10.59429/ersr.v3i1.12208

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1. Introduction

Bangladesh, as one of the fastest-growing industrial economies in South Asia, has experienced a remarkable surge in industrialization over the past few decades. While industrial development has contributed significantly to the country's economic growth, it has also imposed severe environmental burdens, particularly on freshwater ecosystems. One of the most pressing environmental challenges is water pollution caused by untreated industrial wastewater, which is discharged directly into rivers, canals, lakes, and other water bodies without adequate treatment^[1]. This uncontrolled discharge leads to the deterioration of water quality, disruption of aquatic ecosystems, and long-term ecotoxicological consequences.

The major industrial contributors to water pollution in Bangladesh include the textile, tannery, pharmaceutical, food processing, and paper sectors. These industries release a complex mixture of pollutants, including heavy metals such as chromium (Cr), lead (Pb), cadmium (Cd), and arsenic (As); organic compounds like phenols, dyes, and surfactants; and high levels of total dissolved solids (TDS), total suspended solids (TSS), biochemical oxygen demand (BOD), and chemical oxygen demand (COD)^[2]. The physicochemical properties of these effluents, including abnormal pH and elevated temperatures, further exacerbate their harmful effects on aquatic life. Numerous studies have documented that the concentrations of these pollutants frequently exceed both national and international water quality standards, posing serious risks to freshwater organisms and the humans who rely on these water resources for food, drinking water, and livelihoods^[3].

Geographically, several regions in Bangladesh have been identified as pollution "hotspots", where industrial activity is dense and untreated effluents are discharged directly into major rivers. These include Dhaka, Chittagong, Gazipur, Khulna, Narayanganj, and Bogra, which collectively contribute to more than 50% of the country's industrial water pollution load. The ecological impact in these regions is evident, with decreased fish populations, loss of aquatic biodiversity, and the contamination of sediment and water with heavy metals and persistent organic pollutants^[4].

While Bangladesh has established regulatory frameworks such as the Bangladesh Environmental Conservation Act (1995) and the Environmental Conservation Rules (1997) to manage and control industrial pollution, their effectiveness has been limited. Weak enforcement, lack of monitoring, insufficient technical expertise, and financial constraints have resulted in many Effluent Treatment Plants (ETPs) remaining non-functional or partially operational. Consequently, untreated or partially treated wastewater continues to flow into rivers and wetlands, causing cumulative ecological stress over time^[5].

Adding to the challenge are emerging pollutants, such as microplastics, pharmaceuticals, and per- and polyfluoroalkyl substances (PFAS), which are increasingly being detected in industrial effluents and aquatic ecosystems. These contaminants are often persistent, non-biodegradable, and capable of bioaccumulating in aquatic organisms, further exacerbating their ecotoxicological impact. Recent studies in Bangladesh have shown that microplastics are now ubiquitous in freshwater fish and invertebrates, affecting growth, immune function, reproductive success, and overall ecosystem health^[6].

The rapid pace of industrial growth, combined with inadequate wastewater treatment and weak regulatory enforcement, has made industrial wastewater one of the most critical threats to aquatic life in Bangladesh. Understanding the sources, characteristics, and ecotoxicological effects of these effluents is essential for developing effective mitigation strategies and safeguarding the health of freshwater ecosystems. This review aims to synthesize the recent evidence on the composition of industrial wastewater in Bangladesh, its ecotoxicological impacts on aquatic organisms, and the existing challenges and opportunities for environmental management.

2. Methods

This review employed a literature-based approach to assess the ecotoxicological impacts of industrial wastewater on aquatic ecosystems in Bangladesh. Studies published between 2018 and 2025 were the primary focus, supplemented by earlier foundational research to provide context. Relevant literature was identified through systematic searches of databases including PubMed, Google Scholar, ResearchGate, and institutional reports, using keywords such as “industrial wastewater Bangladesh,” “heavy metal pollution,” “textile effluent,” “tannery effluent,” “ecotoxicological impact,” “aquatic life,” and “microplastic pollution.”

Data extraction focused on wastewater characteristics from major industrial sectors, including textile, tannery, paper, food processing, and pharmaceutical industries. Parameters considered included biochemical oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), total suspended solids (TSS), heavy metals, and other organic pollutants. Ecotoxicological effects on aquatic life, such as fish, invertebrates, and plants, were examined to evaluate physiological, reproductive, and developmental impacts. Emerging contaminants, including microplastics and per- and polyfluoroalkyl substances (PFAS), were also included to highlight novel environmental threats.

In addition, studies on regulatory frameworks, including the Bangladesh Environmental Conservation Act (1995) and Environmental Conservation Rules (1997), and the performance of Effluent Treatment Plants (ETPs) and Central Effluent Treatment Plants (CETPs) were analyzed⁶. Mitigation strategies, technological interventions, and capacity-building measures were synthesized to provide insight into potential solutions. All data were organized descriptively to enable qualitative analysis and comparison of pollutant levels, ecological effects, and management approaches. This method allowed for the identification of key industrial contributors, pollution hotspots, regulatory gaps, and challenges in mitigating industrial wastewater impacts on aquatic ecosystems in Bangladesh.

3. Discussion

3.1. Industrial Pollutants in Bangladesh

Industrial growth in Bangladesh over the past few decades has been a key driver of economic development, yet it has also emerged as a major source of environmental pollution. Among the various forms of pollution, water contamination caused by untreated or inadequately treated industrial effluents represents one of the most serious ecological challenges. The rapid expansion of industries, particularly in urban and peri-urban regions, has resulted in substantial volumes of wastewater being discharged directly into rivers, lakes, and wetlands. This has led to widespread degradation of aquatic ecosystems, bioaccumulation of toxic substances, and long-term adverse effects on fish, invertebrates, and plant species. The principal industrial contributors to water pollution in Bangladesh include the textile, tannery, pharmaceutical, food processing, paper, and chemical sectors, collectively accounting for the overwhelming majority of industrial pollution. Analyses based on the modified Industrial Pollution Projection System (IPPS) indicate that the food industry alone is responsible for approximately 42–50% of total industrial water pollution. This is followed by the paper and paper products sector, which contributes around 18–21%, the textile sector at 14–17%, and chemicals and chemical products at 12–17%. Rubber and leather industries also contribute significantly. Taken together, the top five industries are estimated to be responsible for roughly 97% of industrial water pollution in the country⁷.

3.1.1. Textile Industry

The textile industry, as Bangladesh’s largest export-oriented sector, represents the most significant source of industrial wastewater pollution. In 2016, it was estimated that the textile sector generated nearly

217 million cubic meters of wastewater. A substantial proportion of textile factories operate without fully functional Effluent Treatment Plants (ETPs), resulting in the direct release of untreated or partially treated effluent into nearby water bodies. Textile wastewater typically exhibits high levels of Biochemical Oxygen Demand (BOD), with median concentrations around 287 mg/L and peak values reaching 480 mg/L in small-scale operations. Chemical Oxygen Demand (COD) is also elevated, with median values of 747 mg/L and occasional readings up to 970 mg/L⁷. Total Dissolved Solids (TDS) in these effluents often average 2015 mg/L but may exceed 3000 mg/L, while Total Suspended Solids (TSS) frequently surpass 300 mg/L, contributing to turbidity and light attenuation in receiving waters. In addition, heavy metals such as lead, cadmium, and chromium originating from dyes and pigments are commonly detected in textile effluents. These high pollutant loads deteriorate water quality, deplete dissolved oxygen, alter pH, and disrupt photosynthesis in aquatic plants. Numerous studies have documented that textile effluent concentrations often exceed Department of Environment (DOE) permissible limits, posing significant environmental and human health risks^[8].

3.1.2. Tannery Industry

The tannery industry is another major source of water pollution in Bangladesh, primarily due to its high heavy metal and complex chemical content. Following the relocation of tanneries to the Savar Tannery Estate and the establishment of a Central Effluent Treatment Plant (CETP), water pollution levels were expected to decline. However, research has shown that the CETP frequently operates below optimal capacity due to design limitations, inadequate maintenance, and operational inefficiencies. Untreated tannery effluents often contain extremely high chromium concentrations, sometimes exceeding 50,000 mg/L, along with lead concentrations averaging around 32 mg/L^[9]. Phenolic compounds and sulfides are present at levels that surpass the Environmental, Health, and Safety (EHS) guideline limits by several times. TDS and TSS values in tannery effluents are equally alarming, with TDS exceeding 40,000 mg/L and TSS reaching over 14,000 mg/L. These pollutants are highly toxic to aquatic life, bioaccumulate in fish and invertebrate tissues, disrupt endocrine and reproductive systems, and contribute to significant mortality among aquatic organisms. Despite regulatory efforts, tannery effluents continue to exert severe ecological pressure on surrounding water bodies.

3.1.3. Food, Paper, Pharmaceutical, and Chemical Industries

Although the food, paper, pharmaceutical, and chemical industries individually produce lower effluent volumes than textile and tannery operations, their collective contribution to water pollution is substantial. The food industry discharges wastewater rich in organic matter, oils, and fats, resulting in elevated BOD and COD levels. Paper and pulp industries release effluents containing TDS, TSS, and bleaching chemicals, which alter the pH and reduce dissolved oxygen in receiving waters. Pharmaceutical industries generate effluents containing residual chemicals, heavy metals, and active pharmaceutical ingredients (APIs), many of which are poorly treated before discharge. The chemical industry contributes a wide spectrum of inorganic and organic pollutants, including surfactants, dyes, and solvents. Together, these industries exacerbate water quality degradation, reduce biodiversity, and promote eutrophication, leading to long-term ecological imbalance^[10].

3.1.4. Landfill Leachate and Emerging Pollutants

Industrial wastewater is further compounded by landfill leachate from inadequately managed solid waste sites, which contributes additional chemical, organic, and particulate pollution to surface waters. For instance, leachates from the Rajbandh landfill have been reported to exhibit COD concentrations exceeding

10,000 mg/L and TDS levels above 8,000 mg/L, far surpassing safe discharge limits. Emerging contaminants, including microplastics, pharmaceuticals, and per- and polyfluoroalkyl substances (PFAS), are increasingly being detected in rivers, aquatic organisms, and sludge. Microplastics, in particular, have been found at alarming levels in freshwater fish, where they can impair gut health, immune function, and reproductive systems. These pollutants are persistent and bioaccumulative, and they facilitate the transfer of other toxic substances through aquatic food webs, thereby amplifying long-term ecological risks.

Table 1. Comparison of Pollutant Concentrations in Major Industrial Effluents and DOE Standards^[11]

| Parameter | Textile Wastewater | Tannery Wastewater | Food/Paper/Pharma | Landfill Leachate | DOE Standard (Inland Water) |
|------------------------------|--------------------|---------------------|-------------------|-------------------|-----------------------------|
| pH | 6.2–10.2 | 7–9 (CETP effluent) | 5.5–8.5 | 6.5–9 | 6–9 |
| BOD (mg/L) | 287–483 | 730–7600 | 200–500 | 2000–4500 | 50 |
| COD (mg/L) | 747–970 | 2200–22,000 | 500–2000 | 10,000+ | 200 |
| TDS (mg/L) | 2015–3059 | 2130–110,553 | 1000–5000 | 8900+ | 2100 |
| TSS (mg/L) | 200–315 | 1250–14,297 | 150–500 | 1500+ | 150 |
| Chromium (Cr) (mg/L) | 0.5–10 | 8.5–50,282 | 0–2 | 5–50 | 0.05 |
| Lead (Pb) (mg/L) | 0.2–1 | 32 | 0–0.5 | 1–10 | 0.1 |
| Phenols (mg/L) | 1–5 | 50–4000 | 2–20 | 50–200 | 0.5 |
| Surfactants (mg/L) | 10–100 | 5–50 | 2–30 | 20–100 | 0.5 |
| Microplastics (particles/kg) | 500–2000 | 1000–5000 | 300–1000 | 5000+ | N/A |

3.2. Ecotoxicological effects on aquatic life

Industrial effluents and emerging pollutants discharged into freshwater ecosystems in Bangladesh have resulted in widespread ecotoxicological consequences for aquatic life. Rivers, canals, ponds, and wetlands near industrial hubs such as Dhaka, Chittagong, Narayanganj, and Gazipur are heavily contaminated, exposing aquatic organisms—including fish, crustaceans, mollusks, amphibians, and aquatic plants—to multiple stressors simultaneously. These stressors include toxic metals, high organic loads, surfactants, pharmaceutical residues, microplastics, and physicochemical alterations such as reduced dissolved oxygen, pH fluctuations, increased turbidity, and temperature changes^[10]. Collectively, these pollutants impair physiological functions, inhibit growth, alter reproductive capacity, increase mortality, and disrupt trophic interactions, ultimately affecting biodiversity, ecosystem health, and human populations reliant on these water bodies for food and livelihoods.

3.2.1. Heavy Metals

Heavy metals are persistent environmental contaminants that are not biodegradable and can bioaccumulate in aquatic organisms. Metals such as lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni),

mercury (Hg), copper (Cu), zinc (Zn), and aluminum (Al) are commonly found in industrial effluents from textile, tannery, chemical, and pharmaceutical sectors in Bangladesh. Due to their chemical stability, these metals accumulate in sediments and aquatic organisms over time. Fish and invertebrates exposed to heavy metals can experience oxidative stress, disruption of metabolic pathways, endocrine dysfunction, impaired reproduction, developmental abnormalities, and organ toxicity. Lead and cadmium are particularly neurotoxic and nephrotoxic. Chronic exposure in freshwater species has been shown to cause kidney and liver damage, reduced fertility, and impaired larval development^[5]. Hexavalent chromium is highly toxic even at low concentrations, causing gill necrosis, hemolytic anemia, and high mortality in both adult and juvenile fish. Mercury, especially in its methylated form, bioaccumulates in muscle tissue, posing ecological risks and potential human health hazards through fish consumption. Copper and zinc, though essential in trace amounts, become toxic at elevated concentrations, causing enzymatic inhibition, oxidative stress, and behavioral abnormalities. Aluminum, commonly present in industrial and landfill runoff, can interfere with osmoregulation and cause physiological stress^[3].

Table 2. Ecotoxicological Effects of Heavy Metals on Fish and Aquatic Organisms^[12]

| Heavy Metal | Affected Species | Observed Effects |
|---------------|--|--|
| Lead (Pb) | Labeo rohita, Catla catla | Neurotoxicity, reduced fertility, gill damage |
| Cadmium (Cd) | Oreochromis niloticus, Clarias batrachus | Kidney and liver damage, growth inhibition, oxidative stress |
| Chromium (Cr) | Cirrhinus mrigala, Channa punctata | Gill necrosis, hemolytic anemia, mortality |
| Mercury (Hg) | Mystus vittatus, Macrobrachium rosenbergii | Bioaccumulation in muscle, reproductive failure |
| Copper (Cu) | Puntius sophore, Tilapia spp. | Oxidative stress, behavioral changes, growth retardation |
| Zinc (Zn) | Channa striata, Labeo calbasu | Enzymatic inhibition, metabolic disruption |

This table 2 illustrates that heavy metals are among the most hazardous pollutants in freshwater ecosystems. The variety of affected species, including both commercially important fish and benthic invertebrates, highlights the widespread ecological consequences. Lead and cadmium predominantly affect nervous and excretory systems, whereas chromium and mercury target gills, muscles, and reproductive organs. The combined effects reduce population densities, alter community structures, and compromise ecosystem resilience. These findings underscore the need for strict regulation and monitoring of industrial effluents, particularly from tanneries and metal-processing facilities.

3.2.2. Organic Pollutants and Physicochemical Stressors

Apart from heavy metals, organic pollutants and physicochemical stressors from industrial effluents significantly disrupt aquatic ecosystems. Surfactants, dyes, residual pharmaceuticals, and ammoniacal nitrogen are prominent pollutants released from textile, pharmaceutical, and chemical industries. These compounds can compromise cell membrane integrity, interfere with enzyme activity, and disrupt endocrine functions in aquatic organisms. Elevated ammoniacal nitrogen and nitrate levels reduce oxygen availability, creating hypoxic conditions that inhibit growth and survival of fish and invertebrates. High BOD and COD levels further exacerbate oxygen depletion, while shifts in pH and temperature—often a result of industrial discharge—affect metabolic rates, reproduction, and immune responses.

Table 3. Impact of Organic Pollutants and Physicochemical Stressors on Aquatic Life^[6,13]

| Pollutant/Parameter | Species Affected | Effect on Growth/Reproduction/Physiology |
|-------------------------|---|---|
| Surfactants (SDS, LAS) | Labeo rohita, Oreochromis niloticus | Membrane damage, hormonal disruption, impaired growth |
| Ammoniacal Nitrogen | Channa punctata, Clarias batrachus | Hypoxia, reduced survival, gill necrosis |
| High BOD/COD | Puntius sophore, Mystus vittatus | Oxygen depletion, reduced metabolism, increased mortality |
| pH Variation (5–10) | Labeo calbasu, Channa striata | Metabolic disruption, reproductive failure |
| Elevated Temperature | Tilapia spp., Macrobrachium rosenbergii | Stress response, reduced reproductive output |
| Pharmaceutical Residues | Oreochromis niloticus, Cyprinus carpio | Endocrine disruption, altered enzyme activity |

The table 3 demonstrates the multidimensional impacts of organic and physicochemical stressors. Surfactants primarily affect growth and endocrine functions, while high BOD/COD and ammoniacal nitrogen result in hypoxic stress that reduces overall survival. Temperature and pH fluctuations amplify these effects by altering metabolic and reproductive cycles. Pharmaceutical residues introduce endocrine-disrupting compounds that persist in aquatic organisms, highlighting the ecological and human health risk from consumption of contaminated water and fish.

3.2.3. Microplastics and Particulate Pollution

Microplastics, plastic particles less than 5 mm in diameter, have emerged as critical emerging pollutants in Bangladesh’s freshwater ecosystems. They originate from industrial effluents, domestic wastewater, and degradation of larger plastic debris. Fish and invertebrates ingest microplastics, mistaking them for food, which can cause gut obstruction, reduce nutrient absorption, and trigger inflammatory and immune responses. Microplastics also act as vectors for other pollutants such as heavy metals and organic compounds, facilitating their transport within aquatic food webs. Chronic exposure results in stunted growth, reproductive impairments, organ toxicity, and mortality. Importantly, microplastics have been detected in commercially important fish, posing potential human health risks through bioaccumulation and food chain transfer^[9].

Table 4. Effects of Microplastics on Aquatic Life^[14]

| Type of Microplastic | Species Affected | Observed Effects |
|----------------------|--|--|
| Polyethylene (PE) | Labeo rohita, Oreochromis niloticus | Gut obstruction, reduced nutrient absorption, inflammation |
| Polystyrene (PS) | Clarias batrachus, Channa punctata | Oxidative stress, immune suppression, behavioral changes |
| Polypropylene (PP) | Mystus vittatus, Tilapia spp. | Reproductive impairment, bioaccumulation, organ toxicity |
| Microplastic Fibers | Macrobrachium rosenbergii, benthic invertebrates | Reduced feeding efficiency, pollutant transport, mortality |

Microplastics represent a growing ecological threat due to their persistence, ingestion by multiple species, and potential to transport other pollutants. Polyethylene and polystyrene particles primarily affect digestive and immune systems, while polypropylene and fiber fragments are linked to reproductive and developmental impairments. The presence of microplastics in commercially consumed fish emphasizes the urgency of integrating solid waste management, wastewater treatment, and environmental monitoring to prevent further ecological and human health risks.

3.3. Mitigation and Management Strategies

The escalating industrial pollution in Bangladesh's freshwater systems necessitates a comprehensive approach combining regulatory enforcement, technological innovation, and capacity building. Despite the presence of policies such as the Bangladesh Environmental Conservation Act (1995) and Environmental Conservation Rules (1997), enforcement remains weak, and many industries fail to comply with environmental standards. To mitigate the detrimental effects of industrial effluents on aquatic ecosystems and public health, a multi-pronged strategy is essential.

3.3.1. Regulatory Improvements

Regulatory measures form the backbone of pollution control and are critical for ensuring industrial compliance. Strengthening the enforcement of existing laws is imperative. This includes regular inspections of factories, mandatory operational Effluent Treatment Plants (ETPs), and strict penalties for non-compliance. Updating environmental standards to include emerging pollutants such as microplastics, pharmaceutical residues, and per- and polyfluoroalkyl substances (PFAS) is essential, given their growing presence in freshwater systems. Implementing a robust monitoring framework with real-time water quality data collection, remote sensing, and industrial self-reporting mechanisms can improve compliance rates and provide early warnings for pollution spikes^[15]. Additionally, promoting transparency through public reporting and stakeholder engagement encourages accountability and incentivizes cleaner production practices.

3.3.2. Technological Interventions

Technological innovation plays a vital role in reducing pollutant loads before discharge into water bodies. Cleaner Production approaches, which optimize raw material use, energy efficiency, and waste minimization, can significantly reduce wastewater generation. Existing ETPs often operate below efficiency due to inadequate design, insufficient maintenance, or inappropriate treatment methods. Upgrading these plants using advanced technologies such as membrane-based systems (ultrafiltration, nanofiltration, reverse osmosis), advanced oxidation processes (AOPs), and adsorption/ion exchange methods can effectively remove heavy metals, organic pollutants, and emerging contaminants. Furthermore, integrating energy recovery systems, such as Upflow Anaerobic Sludge Blanket (UASB) reactors, can simultaneously treat organic loads and generate biogas, improving economic feasibility. Adoption of decentralized treatment systems, particularly for small and medium-sized enterprises (SMEs)^[16,17], ensures localized pollution control, preventing untreated effluent from reaching major water bodies.

3.3.3. Capacity Building and Awareness

Even the most advanced technologies and regulations are ineffective without trained personnel and public awareness. Industrial staff require specialized training in ETP operation, process optimization, hazard identification, and emergency response to prevent accidental discharges. Public awareness campaigns targeting local communities, industrial stakeholders, and policymakers help foster a culture of environmental responsibility. Promoting water-use efficiency programs, recycling, and sustainable industrial practices

reduces overall wastewater generation and resource consumption. Community-based monitoring initiatives and citizen science projects can supplement government oversight, enabling quicker identification of pollution hotspots.

Table 5. Technological and Management Strategies for Mitigating Industrial Wastewater Pollution^[18,19]

| Strategy | Target Pollutant | Expected Effectiveness | Challenges/Limitations |
|--|--|--|--|
| Regulatory Enforcement & Updated Standards | Heavy metals, BOD, COD, TDS, emerging pollutants | High, ensures compliance, reduces effluent loads | Weak governance, corruption, limited inspection capacity |
| Cleaner Production (Process Optimization) | BOD, COD, TDS, surfactants, dyes | Moderate to high, reduces pollutant generation at source | Requires industrial investment, staff training |
| Effluent Treatment Plant Upgrades (Membrane Technology, AOPs, Adsorption/Ion Exchange) | Heavy metals, organic pollutants, microplastics | High, effective pollutant removal | High capital and operational cost, maintenance requirements |
| Energy Recovery Systems (UASB, Biogas Recovery) | Organic pollutants (high BOD/COD) | Moderate to high, reduces organic load and produces energy | Design complexity, operational expertise required |
| Decentralized Treatment for SMEs | Heavy metals, BOD, COD | Moderate, localized pollution control | Requires coordination, regulatory support, funding |
| Capacity Building & Staff Training | All pollutant types | High, improves operational efficiency and compliance | Time-intensive, needs continuous updates |
| Public Awareness & Community Monitoring | Emerging pollutants, microplastics | Moderate, encourages sustainable practices | Limited reach in rural areas, needs government and NGO support |

The table 5 highlights the complementary nature of regulatory, technological, and social interventions. While regulatory enforcement ensures compliance and sets standards, technological interventions physically reduce pollutant loads. Cleaner Production and ETP upgrades directly reduce effluent toxicity, while energy recovery adds economic incentives. Capacity building and public awareness create the human capital necessary for sustainable operations and community oversight. Challenges such as high costs, limited technical expertise, weak governance, and insufficient SME compliance remain barriers^[20]. Therefore, an integrated approach combining all strategies is essential to achieve significant reductions in industrial wastewater pollution in Bangladesh.

4. Challenges and future directions

The mitigation of industrial water pollution in Bangladesh faces multiple structural, financial, and scientific challenges. Despite the existence of policies and technological interventions, persistent pollution, emerging contaminants, and socio-economic constraints continue to hinder effective management. Addressing these challenges requires coordinated governance, strategic investment, and targeted research to safeguard freshwater ecosystems and public health.

4.1. Weak Governance and Enforcement

A major obstacle to effective pollution control in Bangladesh is the weak enforcement of environmental regulations. Although the Bangladesh Environmental Conservation Act (1995) and Environmental Conservation Rules (1997) provide a legal framework for wastewater management, compliance monitoring is inconsistent and often inadequate. Many industries continue to operate without functional Effluent Treatment Plants (ETPs), and regulatory inspections are sporadic due to limited manpower, insufficient technical expertise, and inadequate resources within the Department of Environment (DOE). Corruption, lack of transparency, and minimal penalties for non-compliance exacerbate the issue, allowing untreated or partially treated effluents to be discharged into rivers, lakes, and wetlands^[21]. This ongoing pollution threatens ecological integrity, diminishes biodiversity, and increases human health risks through consumption of contaminated water and fish. Strengthening institutional capacity, enhancing inspection frequency, and integrating community-based monitoring systems are critical steps to improve regulatory compliance and reduce industrial water pollution.

4.2. High Operational Costs and SME Limitations

Operational and maintenance costs of advanced wastewater treatment technologies represent another significant challenge, especially for small and medium-sized enterprises (SMEs). While large industries may have the financial capacity to implement membrane-based systems, advanced oxidation processes, or adsorption techniques, many SMEs cannot afford such solutions or lack the technical expertise to operate them efficiently. Even where centralized Effluent Treatment Plants (CETPs) exist, SMEs frequently fail to connect or comply due to technical issues, irregular monitoring, and lack of trained personnel. Additionally, high energy consumption and chemical usage further limit the feasibility of sustaining effective wastewater treatment^[22,23]. To address these constraints, targeted subsidies, the development of low-cost treatment alternatives, shared CETP facilities, and public-private partnerships providing technical and financial support are essential for improving compliance among SMEs.

4.3. Emerging Pollutants: Microplastics and PFAS

Emerging pollutants, including microplastics and per- and polyfluoroalkyl substances (PFAS), present a growing ecological and public health concern in Bangladesh. Microplastics have been increasingly detected in freshwater fish, invertebrates, and sediments, where they disrupt feeding, reproduction, and immune function. PFAS, widely used in textiles, coatings, and industrial processes, are highly persistent, bioaccumulative, and resistant to conventional wastewater treatment^[24]. The lack of regulatory standards, standardized monitoring protocols, and effective treatment technologies for these pollutants leaves aquatic ecosystems vulnerable to chronic exposure. Addressing these challenges requires the development of analytical methods for detecting emerging pollutants, establishing permissible limits, and implementing advanced treatment technologies specifically designed to remove microplastics and PFAS from industrial effluents^[25].

4.4. Research Gaps and Recommendations

Critical knowledge gaps limit the development of evidence-based policies and effective mitigation strategies. Current research in Bangladesh on the fate, transport, and cumulative impacts of industrial pollutants on aquatic ecosystems and human health is limited. Longitudinal studies examining chronic exposure, bioaccumulation, and trophic transfer are scarce, and there is insufficient evaluation of the feasibility and effectiveness of low-cost or decentralized treatment technologies suitable for SMEs^[26]. Future research should focus on identifying pollution hotspots, evaluating innovative and cost-effective treatment methods, and assessing ecological and human health risks associated with emerging contaminants.

Collaborative efforts involving government agencies, academic institutions, and industrial stakeholders are essential for developing sustainable, locally appropriate solutions. Integration of environmental monitoring with geographic information systems (GIS) and real-time data platforms can further enhance decision-making and provide early warning for pollution events, facilitating proactive mitigation strategies^[27].

In conclusion, the challenges facing industrial water pollution management in Bangladesh are multifactorial, encompassing governance weaknesses, economic constraints, technological limitations, and knowledge gaps. Effective mitigation will require an integrated approach that strengthens institutional enforcement, supports SMEs with affordable and efficient treatment solutions, monitors emerging pollutants, and addresses critical research needs. Forward-looking strategies that combine regulatory reform, technological innovation, stakeholder engagement, and adaptive management are essential to ensure the long-term protection of freshwater ecosystems and public health.

5. Conclusion

Industrial wastewater in Bangladesh poses significant ecotoxicological threats to freshwater ecosystems, driven by elevated levels of heavy metals, organic pollutants, and emerging contaminants such as microplastics. These pollutants disrupt the growth, reproduction, physiology, and immune functions of aquatic organisms, leading to biodiversity loss, reduced fish productivity, and compromised ecosystem stability. Despite the presence of legal frameworks and regulatory standards, weak enforcement, non-functional or inefficient Effluent Treatment Plants (ETPs), and technological limitations exacerbate pollution and limit effective mitigation. Addressing this challenge requires a multi-pronged approach, including stringent policy enforcement, adoption of advanced wastewater treatment technologies, enhanced industry compliance, capacity building for industrial staff, and systematic monitoring of emerging contaminants. Coordinated efforts by government agencies, industrial stakeholders, researchers, and international partners are essential to safeguard Bangladesh's aquatic ecosystems, protect public health, and ensure sustainable management of water resources for future generations.

Conflict of interest

The authors declare no conflict of interest

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