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Sustainable Practices in Bangladesh's Textile Industry: Evaluating Effluent Treatment Impact on Water Quality and Environmental Health

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Abstract. Significant environmental challenges posed by wastewater discharge from Bangladesh's vital textile sector were evaluated. The performance of effluent treatment plants (ETPs) in Dhaka's export processing zone was critically evaluated using Z-score analysis of key water quality parameters such as TDS, BOD, COD, pH and heavy metals measured at both inlet and outlet points. ETPs demonstrated efficacy in pH stabilization, DO enhancement and organic pollutant reduction, however, persistent TDS exceedances, despite general compliance with Bangladesh's environmental conservation rules (ECR) 1997, signaled a critical threat to soil and aquatic ecosystems. General compliance with ECR 1997 was largely achieved but persistent TDS exceedances were observed in later samples. High TDS concentrations raised concerns regarding soil degradation, aquatic toxicity and potential threats to human health. Enhanced filtration technologies and stricter monitoring were identified as necessary to address these high TDS concentrations and prevent further ecological disruption. The critical role of optimized ETP operations in ensuring sustainable industrial practices, maintaining regulatory compliance and protecting environmental and public health within Bangladesh's textile industry was highlighted. To address these findings, a shift towards a data-driven, proactive management framework centered on dynamic key performance indicators (KPIs) was proposed. These KPIs, incorporating real-time monitoring, statistical process control and pollutant-specific targets aligned with local ecological risks, were designed to enable predictive compliance and drive sustainable innovation. The integration of economic, ecological and social impact assessments, alongside rigorous long-term monitoring and adaptive policy mechanisms, was recommended to ensure the textile industry's growth is both environmentally sound and economically viable, fostering a resilient and sustainable future for Bangladesh.

Keywords: effluent treatment plants (ETPs), Bangladesh textile industries, water quality, TDS, environmental compliance, sustainable practices

Introduction

Bangladesh has emerged as a major force in the global garment industry, ranking as the world's second-largest exporter. This remarkable growth highlights the country's economic resilience and adaptability, particularly in overcoming challenges to excel in the textile and garment sectors (The Daily Star, 2024). However, this success has also led to significant environmental and health risks, primarily due to the discharge of untreated wastewater from textile factories.

The textile industry is vital to Bangladesh's economy, with ready-made garments (RMG) contributing approximately USD 28.67 Billion in 2016, accounting for about 82% of the nation's export revenue. The sector employs over four Million people, most of whom are women, across more than 4,000 factories (Hossain *et al*., 2018). Despite its economic importance, the industry's rapid expansion has resulted in substantial environmental challenges, particularly due to the large-scale discharge of chemically contaminated wastewater into rivers. This wastewater often exceeds national regulatory limits and severely impacts aquatic ecosystems (Kamal, 2016).

Untreated wastewater from textile processes, especially dyeing and printing, contains high levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD), depleting oxygen in aquatic ecosystems. Additionally, dyes and heavy metals such as chromium and copper increase water alkalinity and disrupt biological

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processes in treatment facilities (Textile School, 2024). Effluent treatment plants (ETPs) play a crucial role in managing wastewater from the textile industry and mitigating environmental damage. According to the department of environment (DoE, 2008), more than fifty percent of Bangladesh's export-oriented industries have established ETP facilities, while many smaller enterprises lack the resources to implement high-quality treatment systems (Begum *et al*., 2020; Islam and Mostafa, 2020). Many of these smaller industries, particularly those serving local markets, cannot afford to construct high-quality ETP plants due to financial constraints (Pérez-González *et al*., 2012).

Monitoring water quality is essential for ensuring safe drinking water and improving water management (Murei *et al*., 2024). To make informed decisions regarding the protection and management of water reservoirs, water quality characterization data is collected to assess the extent of contamination (Din *et al*., 2023). Effective wastewater treatment is critical to complying with environmental regulations, reducing pollution in local water bodies and safeguarding public health, while the initial cost of establishing ETPs may be high, the long-term benefits such as avoiding fines, conserving resource and enhancing industry reputation underscore their importance in promoting sustainable practices (Kingsley Group, 2024).

Despite their significance, the efficiency of ETPs varies, necessitating continuous monitoring and assessment of water quality standards. This study aims to evaluate the effectiveness of ETPs in reducing key water quality parameters such as TDS, BOD, DO, TSS, COD, heavy metals, Mn, chloride and pH across multiple factories within a major industrial zone in Bangladesh. By identifying gaps in current treatment methods and compliance issues, the research provides recommendations to improve wastewater management practices, ensuring environmental protection and the sustainable growth of Bangladesh's textile industry.

Textile dyes and environmental impacts. Textile dyes, essential for adding colour to garments are soluble organic compounds that are difficult to remove using conventional treatment methods due to their high solubility in water (Mahapatra, 2016). These dyes classified as reactive, direct, basic and acidic darken water, reduce light penetration, alter aquatic photosynthesis and lower dissolved oxygen levels (Hassan and Carr, 2018). Their complex molecular structures, consisting of chromophore and auxochrome groups, enable strong binding to fibres but make their removal from wastewater particularly challenging (Wardman, 2017; Shamey and Zhao, 2014).

The textile manufacturing process relies heavily on water for washing and dyeing, leading to additional environmental concerns, including air pollution from volatile chemicals and the generation of solid waste (Muthu, 2017; Bhatia, 2017). Most wastewater from the textile industry contains high concentrations of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) (Setiadi *et al*., 2006). Notably, non-biodegradable organic compounds, particularly textile dyes, are a major concern (Orts *et al*., 2018). The discharge of untreated effluent into aquatic ecosystems alters key water quality parameters, including BOD, COD, total dissolved solids (TDS), total suspended solids (TSS) and pH levels. The release of untreated effluents poses a severe threat to both aquatic life and human health (Garg *et al*., 2022; Islam *et al*., 2022).

Textile industry wastewater is highly polluted, exhibiting extreme pH variations (5.63-11.56), intense coloration (upto 8,500 Pt-Co) and high TDS levels (upto 10,710 mg/L), all of which exceed regulatory limits. Elevated BOD (1,160 mg/L) and COD (3,600 mg/L) levels indicate significant organic and chemical loads. Additionally, low dissolved oxygen (DO) levels and high turbidity suggest poor water quality, posing serious risks to aquatic organisms (ECR, 1997).

High concentrations of textile dyes in aquatic environments impair water re-oxygenation and block sunlight, disrupting biological processes such as the photosynthesis of algae and other aquatic species. Due to their environmental persistence and potential to degrade into carcinogenic or mutagenic compounds, dyes present long-term ecological risks (Waterman Engineers Australia, 2024). A sustainable solution for wastewater treatment involves using naturally occurring raw clay and its organo-modified counterpart for the adsorption of organic pollutants. This approach minimizes chemical waste and provides an energy-efficient, cost-effective remediation process (Mansouri *et al*., 2025).

Water contamination and health risks. Textile dyes are often toxic, mutagenic and carcinogenic, posing significant health risks. These pollutants accumulate through the food chain, contaminating local water supplies and affecting higher trophic levels (Newman, 2019; Khatri *et al*., 2018; Aquino *et al*., 2014). Dutta *et al*. (2024) noted that dyes are primarily used to colour textiles, as well as materials like leather, fur and plastics. Azo dyes, widely used in textile production are particularly concerning, as 15-50% of the dye fails to bind to fabrics and ends up in wastewater. In many developing countries, textile wastewater is sometimes used for agricultural irrigation, further disrupting soil microbial populations and hindering plant growth (Rehman *et al*., 2018; Imran *et al*., 2015). Many developing countries are especially vulnerable to water scarcity, a challenge further intensified by unplanned population growth. Studies indicate that contaminated food and water consumption has resulted in over five million fatalities, primarily in developing nations (Ondieki *et al*., 2021). Globally, an estimated 12-15% of textile dyes are lost during manufacturing and discharged into wastewater, exacerbating environmental contamination. These dyes increase BOD and COD levels, obstruct photosynthesis, inhibit plant growth and contribute to bioaccumulation and toxicity (Baly, 2022).

Water contamination and inadequate sanitation remain critical public health concerns worldwide. Approximately 3.6 Billion people lack access to properly maintained sanitation, while nearly 2 Billion do not have safe, readily available water at home. Poor sanitation, hygiene, and waterborne diseases contribute to around 6,000 child fatalities daily (UNICEF/WHO, 2014, 2021). The lack of access to microbiologically safe drinking water and inadequate sanitation has jeopardized the well-being of 10 Million people, leading to diseases such as diarrhea, salmonellosis, skin infections, cholera, dysentery and various gastrointestinal, neurological and reproductive disorders, resulting in high morbidity and mortality rates (Akhtar *et al*., 2019).

Heavy metal contamination and ecosystem disruption. Heavy metals, including chromium, lead and cadmium, are significant pollutants in textile effluents, contributing to environmental degradation. These metals, both essential (e.g. Mg, Fe, Zn) and non-essential (e.g. Cr, Pb), accumulate in soils and water bodies, causing long-term ecological harm (Moloi *et al*., 2020). When present in wastewater, these metals can be absorbed by crops, posing risks to human and animal health (Snyman *et al*., 2006; Mapanda *et al*., 2005). Chronic exposure to metal-rich dyes disrupts ecosystem structures, affecting biodiversity and human health through bioaccumulation (Rawat *et al*., 2016; Ito *et al*., 2016). Chromium for example, induces oxidative stress, impeding plant growth and photosynthesis and reducing CO_2 uptake (Copaciu *et al*., 2013).

This study investigates the effectiveness of textile wastewater treatment, evaluating key water quality indicators such as pH, DO, TDS, BOD, COD, chloride, manganese and CO_2 to ensure compliance with environmental and health standards. It examines physical and chemical parameters at various points (inlet, outlet and downstream) to assess treatment efficiency and potential environmental consequences. The research also explores the impact of textile effluents on human health and biodiversity, focusing on pollutants like heavy metals and dyes. Emphasis is placed on the significance of proper wastewater treatment to safeguard public health and environmental integrity.

Despite the critical role of effluent treatment plants (ETPs) in reducing pollutants, including pH, DO, chloride, manganese and CO_2, Bangladesh's textile industry struggles with managing high levels of total dissolved solids (TDS), biochemical oxygen demand (BOD) and chemical oxygen demand (COD), which often exceed regulatory limits. The existing literature lacks comprehensive analysis of the operational efficiencies of ETPs, particularly in reducing TDS levels. Additionally, there is insufficient exploration of the integration of advanced treatment technologies such as zero liquid discharge (ZLD) systems. This creates a critical research gap in understanding how ETPs can be optimized to fully meet environmental standards and effectively address high pollutant levels, particularly TDS, to protect both public health and the environment.

Objectives. The primary objectives of this research are to evaluate the effectiveness of existing effluent treatment plants (ETPs) in reducing critical wastewater parameters such as TDS, BOD, COD, pH and DO. The study also aims to investigate the impact of high TDS levels on water quality, ecosystems and public health in Bangladesh's textile industry. Furthermore, it seeks to assess the potential of advanced wastewater treatment technologies, such as zero liquid discharge (ZLD) systems and enhanced filtration methods, to achieve further reductions in pollutants and meet environmental standards. Based on these findings, the research will recommend improvements in wastewater management practices, focusing on treatment optimization, regulatory enforcement and sustainable development within the textile sector.

Studied area selection and sample collection. This study was conducted in Dhaka export processing zone 2 (EPZ 2), located in Gonakbari, Savar, Dhaka, a highly industrialized region hosting numerous textiles dyeing factories that discharge wastewater into surrounding water bodies. The research aimed to assess the environmental and public health impacts of untreated or inadequately treated wastewater from these facilities. Data collection on September 15, 2023, provided a performance snapshot of effluent treatment plants (ETPs) across various enterprises, including M/s. LSI industries Ltd. (electroplating section), M/s. Paddocks Jeans Ltd., M/s. Flagship Dhaka CETP (BD) Ltd., M/s. Redpoint Jackets Ltd., M/s. Savar dyeing and finishing industry Ltd., M/s. EOS textile mills Ltd., M/s. Daeyu Bangladesh Ltd. and M/s. YKK Pte (BD) Ltd. Figure 1 presents a detailed map of Dhaka Export Processing Zone 2 (EPZ 2), strategically located in Gonakbari, Savar, Dhaka.

Strategically selecting BEPZA (Bangladesh export processing zone authority) areas in Savar and Gonakbari for this study enabled an in-depth analysis of both environmental and human health effects, given the high concentration of industrial activities near residential communities. Sample collection focused on water quality parameters from multiple points, including discharge outlets near factories, nearby rivers and local water sources used for drinking and irrigation. Samples were collected from both inlet (pre-treatment) and outlet (post-treatment) points, emphasizing pollutants like pH, dissolved oxygen (DO), total dissolved solids (TDS),

Fig. 1. Detailed map of Dhaka export processing zone 2 (EPZ 2) in Gonakbari, Savar, Dhaka, highlighting industrial sites, water sampling points and surrounding residential areas.

biochemical oxygen demand (BOD), chemical oxygen demand (COD), chloride and manganese. These analyses aimed to establish connections between industrial wastewater discharge and health issues such as skin diseases and respiratory problems in local populations, providing a comprehensive evaluation of the environmental and public health impacts of Bangladesh's textile dyeing industry. This research also included a comprehensive physical, chemical and biological analysis of wastewater collected from the outlet of the ETP, with all analyses conducted within 2 to 3 days of sample collection.

Materials and Methods

This study utilized various standardized methods to assess critical water quality indices. pH was measured (APHA, 2012, 4500 H+B) *via* a potentiometric approach using a benchtop pH meter to capture immediate readings pre- (inlet) and post-treatment (outlet). Biochemical oxygen demand (BOD_5) was evaluated over a five-day incubation at 20 °C (APHA, 2012, 5220B), assessing the impact of organic load on dissolved oxygen levels. Chemical oxygen demand (COD) was determined (APHA, 2012, 5220B) by calculating the oxygen required to oxidize both organic and inorganic compounds, thus indicating pollution levels. Total dissolved solids (TDS) were measured (APHA, 2012, 2540 C) by drying filtered samples to quantify dissolved chemicals impacting water quality. Total suspended solids (TSS) was determined by filtering, drying and weighing samples to measure solid particles. Furthermore, ammoniacal nitrogen (NH_3-N), indicating both free NH_3 and NH_4 in wastewater was measured using USEPA method 350.2, with chloride and manganese concentrations determined by APHA methods (4500-Cl and 3500-Mn, respectively). The equation used for wastewater analysis employs the Z-score method, $Z = (X - \mu) / \sigma$ ..... 1) (Nowdo *et al*., 2021).

where:

X = represents the observed value of the parameter, μ is the mean or regulatory limit for the parameter (in this context, the ECR 1997 standard for each wastewater parameter) and σ denotes the standard deviation of the regulatory limit. When only a limit range is provided, the midpoint of the range may serve as an approximation for μ, while an assumed deviation, often based on a permissible threshold, may be used in place of σ.

Results and Discussion

Comprehensive analysis of physical, chemical and biological parameters in wastewater from the effluent treatment plant (ETP). ***Evaluation of three outlet samples with emphasis on compliance with ECR 1997 standards and key insights for improved TDS management (based on Tables 1, 2 and 3 and depicts in Figure 2, 3 and 4 respectively).*** Figure 2 and Table 1 presented that wastewater analysis from the ETP outlet meets ECR 1997 standards, with operative parameters like pH, DO (5.9 mg/L), BOD_5 (30 mg/L) and COD (84 mg/L) within safe limits, supporting environmentally safe discharge. The total dissolved solids (TDS) level (155 mg/L) is significantly below the allowable limit of 2100 mg/L, reflecting excellent reduction of dissolved solids. Likewise, the total suspended solids (TSS) (40.7 mg/L) and chloride (39 mg/L) are well within safe limits, indicating effective filtration and low salt content. Heavy metals like manganese (Mn) (0.552 mg/L) and nutrients such as ammoniacal nitrogen (NH_3-N) (0.39 mg/L) are far below their respective permissible limits, reducing risks of toxicity to aquatic life and preventing issues such as eutrophication. In general, the wastewater treatment is performing efficiently, making the water suitable for safe discharge or potential reuse, with minimal risk to human health, aquatic ecosystems and the environment.

Table 1. Physical, chemical and biological analysis of wastewater, sources: outlet of ETP

Wastewater test parameter	Concen-tration	Unit	ECR 1997 Standard for wastewater
pH	7.4	mg/L	6-9
DO	5.9	mg/L	4.5-8
BOD_5	30	mg/L	50
COD	84	mg/L	200
TDS	155	mg/L	2100
TSS	40.7	mg/L	150
Chloride	39	mg/L	600
Mn	0.552	mg/L	5
Ammoniacal-nitrogen (NH_3-N)	0.39	mg/L	50

The analysis of wastewater from the effluent treatment plant (ETP) presented in Fig. 3 and Table 2 indicates that most parameters meet the ECR 1997 standards for wastewater discharge. The pH (7.3), dissolved oxygen (6.1 mg/L), biochemical oxygen demand (BOD5) (20 mg/L) and chemical oxygen demand (COD) (26 mg/L) all fall well within permissible limits, showing that the treatment process effectively neutralizes the water, supports aquatic life and reduces organic and chemical pollutants. The total suspended solids (TSS) level of 75.5 mg/L is also within the acceptable range and chloride concentration (52 mg/L) is significantly below the limit, indicating minimal salt contamination. Manganese (1.115 mg/L) and ammoniacal-nitrogen (0.85 mg/L) are both well below their respective limits, reflecting low toxicity and nutrient pollution. However, the total dissolved solids (TDS) level of 2480 mg/L exceeds the standard limit, suggesting that further filtration may be required to fully meet environmental safety guidelines. Overall, the wastewater is treated effectively, posing minimal risks to human health and the environment, though additional attention to TDS is recommended.

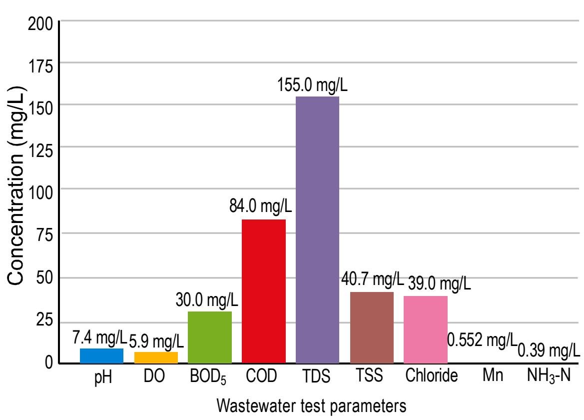

Fig. 2. Concentration levels of selected wastewater parameters from the ETP corresponding outlet.

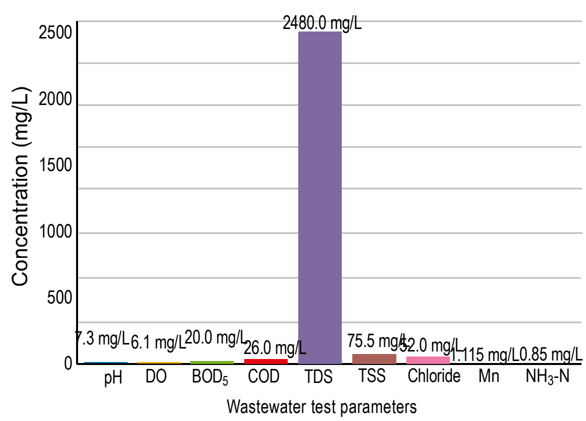

Fig. 3. Concentration levels of selected wastewater parameters from the ETP corresponding outlet.

Table 2. Physical, chemical and biological analysis of wastewater, sources: outlet of ETP

Wastewater test parameter	Concen-tration	Unit	ECR 1997 Standard for wastewater
pH	7.3	mg/L	6-9
DO	6.1	mg/L	4.5-8
BOD_5	20	mg/L	50
COD	26	mg/L	200
TDS	2480	mg/L	2100
TSS	75.5	mg/L	150
Chloride	52	mg/L	600
Mn	1.115	mg/L	5
Ammoniacal nitrogen (NH_3-N)	0.85	mg/L	50

Table 3. Physical, chemical and biological analysis of wastewater, sources: outlet of ETP

Wastewater test parameter	Concen-tration	Unit	ECR 1997 Standard for wastewater
pH	8	mg/L	6-9
DO	5.8	mg/L	4.5-8
BOD_5	20	mg/L	50
COD	38	mg/L	200
TDS	2540	mg/L	2100
TSS	44.5	mg/L	150
Chloride	39	mg/L	600
Mn	0.585	mg/L	5
Ammoniacal-nitrogen (NH_3-N)	ND	mg/L	50

The analysis of wastewater from the effluent treatment plant (ETP) depicts in Fig. 4 and Table 3 demonstrates that most parameters comply with the ECR 1997 standards for safe discharge, while highlighting a few areas that may require further attention. The pH of 8 falls within the permissible range of 6 to 9, indicating balanced acidity and alkalinity suitable for discharge. Dissolved oxygen (DO) at 5.8 mg/L, well within the 4.5 to 8 mg/L range, suggests that the water can support aquatic life. Both biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) values are 20 mg/L and 38 mg/L, respectively, significantly below their respective limits of 50 mg/L and 200 mg/L, pointing to effective reduction of organic and chemical pollutants. However, the total dissolved solids (TDS) concentration of 2540 mg/L exceeds the acceptable limit of 2100 mg/L, indicating potential concerns about dissolved substances that may require enhanced treatment. The total suspended solids (TSS) level of 44.5 mg/L is within safe limits, while the chloride concentration (39 mg/L) is well below the permissible limit of 600 mg/L, indicating low salt contamination. Manganese (Mn) concentration of 0.585 mg/L is also well within the acceptable range of 5 mg/L. The absence of detectable ammoniacal nitrogen (NH_3-N) suggests minimal nutrient pollution, further supporting the effectiveness of the treatment. While global compliance is strong, the elevated TDS levels may require further mitigation to ensure the treated wastewater aligns fully with environmental and health safety standards.

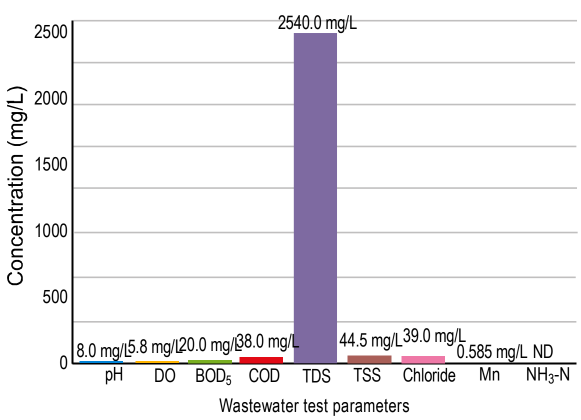

Fig. 4. Concentration levels of selected wastewater parameters from the ETP corresponding outlet.

Z-Score analysis of ETP wastewater quality was conducted to assess compliance with ECR 1997 standards, focusing on key parameters based on Figures 2-4 from Tables 1-3. The Z-scores were calculated using equation 1. The Fig. 2 (Isolated from Table 1) presents the concentrations of key wastewater parameters from the effluent treatment plant (ETP), highlighting compliance with environmental standards and identifying potential deviations. Total dissolved solids (TDS) exhibits a positive Z-score of 2.10, marking it as an outlier despite remaining within regulatory limits. This elevated TDS suggests it is a crucial parameter to monitor for ongoing compliance. Other parameters, including pH, BOD_5 and COD, have concentrations near the mean and fall well within ECR 1997 standards, indicating strong control over organic and chemical pollutants. Manganese (Mn) and ammoniacal-nitrogen (NH_3-N) show low concentrations with negative Z-scores, reflecting efficient reduction to minimal levels. Eventually, the ETP demonstrates success in effectively treating contaminants, with TDS flagged for careful monitoring.

The Z-score analysis in Fig. 3 (Isolated from Table 2) of the ETP outlet showed that most of the parameters meet ECR (1997) standards. The pH level of 7.3 and DO at 6.1 mg/L comfortably fall within acceptable ranges, while BOD_5 and COD, at 20 mg/L and 26 mg/L respectively, are notably below their limits, reflecting efficient reduction of organic and chemical demand. However, TDS at 2480 mg/L has a slight positive Z-score, exceeding the 2100 mg/L standard and indicating a potential concern. Other parameters, such as TSS (75.5 mg/L), chloride (52 mg/L), manganese (1.115 mg/L) and ammoniacal nitrogen (0.85 mg/L) have negative Z-scores, suggesting they are well within limits. Except for the minor TDS exceeds of standard level, the wastewater quality largely complies with regulatory standards.

The Z-score analysis of (Fig. 4) (Isolated from Table 3) displayed that the most of wastewater characteristics align with ECR 1997 standards. Parameters including pH, DO, BOD, COD, TSS, chloride, manganese and ammoniacal nitrogen have negative or near-zero Z-scores, signaling compliance. However, TDS again shows a positive Z-score, slightly above the 2100 mg/L limit, signaling a need for attention. Aside from TDS, all other parameters demonstrate regulatory compliance, suggesting strong environmental safety.

Summary of Fig. 5. *Based on Fig. 2-4*. A comprehensive overview of wastewater quality compliance with Bangladesh's ECR 1997 standards is provided by the synthesized Z-score analysis from Tables 1-3, with a specific focus on Fig. 4 (Table 3). In (Fig. 4), the effluent treatment plant (ETP) outlet data reveals that for most parameters, the ETP effectively maintains compliance. Specifically, pH was measured at 8 mg/L (ECR 6-9), DO at 5.8 mg/L (ECR 4.5-8), BOD_5 at 20 mg/L (ECR 50), COD at 38 mg/L (ECR 200), TSS at 44.5 mg/L (ECR 150), Chloride at 39 mg/L (ECR 600) and Mn at 0.585 mg/L (ECR 5) all well within regulatory limits, indicating effective organic matter and particulate removal and reduced contamination risks. However, a critical deviation was observed in TDS levels, with (Fig. 4), showing a concentration of 2540 mg/L, significantly exceeding the ECR 1997 standard of 2100 mg/L, signaling potential environmental risks like soil salinization and aquatic toxicity. The not detected (ND) NH_3-N in (Fig. 4), requires clarification, though low NH_3-N in other Figures suggests effective ammonia control. The Z-score analysis across Tables 1-3 supports strong regulatory alignment for most parameters but the significant TDS exceedance in (Fig. 4) and a slight TSS increase in later samples, necessitates continued monitoring and process optimization. Further clarification of the NH_3-N result is also recommended to ensure comprehensive environmental safety and compliance.

Environmental and operational impacts of elevated total dissolved solids (TDS) in wastewater. Elevated total dissolved solids (TDS) in wastewater pose notable environmental and operational risks, particularly when levels exceed regulatory standards. High TDS concentrations reflect increased dissolved minerals, salts and other inorganic substances, which can alter the chemical profile of receiving water bodies. This shift can impact aquatic ecosystems by reducing water clarity, disrupting photosynthesis and inducing osmotic stress in aquatic life. Elevated TDS levels also risk soil salinization if wastewater is used for irrigation, diminishing soil fertility over time.

In industrial settings, high TDS contributes to scaling and corrosion in pipelines and equipment, leading to increased maintenance costs and reduced operational efficiency. Untreated, these dissolved solids compromise treated effluent quality, affecting both local and downstream water resources. Addressing high TDS sources such as, specific industrial discharges or chemical additives can optimize treatment processes, ensuring that TDS levels remain within regulatory limits, thereby promoting environmental and operational sustainability.

TDS as a key indicator of wastewater composition and potential compliance issues. *Z-score analysis*

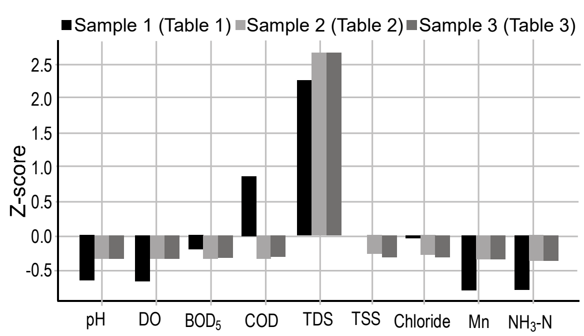

Fig. 5. Bar chart of Z-score analysis for wastewater parameters from the effluent treatment plant (ETP) isolated from Fig. 2, 3 and 4. Positive and negative Z-scores indicate the extent of deviation from ECR 1997 standards, with parameters such as TDS showing notable positive deviations in Tables 2 and 3.

across Tables 2-4. In Table 1, TDS displays a high Z-score, signaling a significant deviation from the mean concentration while remaining within regulatory limits, identifying TDS as a major component of the sample. COD also has a positive z-score, albeit less pronounced, indicating moderate deviation. Parameters like pH, DO, and Chloride have z-scores near zero or below, suggesting stability within typical wastewater composition ranges.

Table 2 shows an even higher TDS z-score, marking it as a more distinct outlier. This increase suggests potential compliance issues as TDS surpasses the standard limit, indicating a need for closer monitoring and intervention. Other parameters, such as pH, DO and Mn, maintain near-zero or negative z-scores, reflecting stability. COD and BOD_5 exhibit modest positive Z-scores, contributing slightly above average to the composition.

In Table 3, TDS reaches its highest z-score, underscoring a pronounced deviation from the mean and signaling the need for regulatory focus. COD's Z-score has slightly increased, indicating a modest rise, while parameters like pH and DO maintain stable Z-scores near zero or slightly negative. The consistently high TDS Z-scores across all Figures highlight it as a persistent concern, suggesting the necessity for enhanced treatment processes to manage dissolved solids effectively.

Escalating TDS levels: *environmental risks and compliance concerns.* The Z-score analysis of total dissolved solids (TDS) across Tables 1-3 highlights an escalating trend in TDS levels, with substantial deviations from the mean in each data-set. In Table 1, the TDS concentration of 155 mg/L results in a moderate Z-score of approximately 2.26, signaling it as a prominent component but within manageable environmental limits. However, in Table 2, TDS jumps to 2480 mg/L, producing a much higher Z-score and surpassing the ECR 1997 standard limit of 2100 mg/L. This significant deviation suggests an alarming concentration of dissolved solids, which can lead to environmental stress by increasing water salinity and potentially harming aquatic organisms through osmotic imbalances. The trend intensifies in Table 3, where TDS reaches 2540 mg/L, yielding the highest Z-score and marking it as an extreme outlier. Persistently high TDS levels at this concentration can impair water quality, making it unsuitable for agricultural and industrial use, while also threatening biodiversity in natural water bodies.

The consistent upward trend in TDS Z-scores across the Tables indicates a pressing environmental concern, suggesting that treatment processes may be inadequate in managing dissolved solids. High TDS levels can alter the water chemistry, affecting species that are sensitive to salinity, reducing oxygen levels and potentially fostering algal blooms. Addressing this trend is essential to mitigate ecological harm and ensure the wastewater meets environmental standards, emphasizing the need for improved treatment processes and ongoing monitoring to protect aquatic ecosystems and water quality (Garg *et al*., 2022).

Analysis of physical characteristics in wastewater from textile industry inlet and outlet points in selected factories. The Fig. 6 and (Table 4) revealed that the pH levels at the inlet are consistently high, ranging between 10 and 11, whereas the outlet pH stabilizes between 7.8 and 8.2, while WHO recommends a pH range of 6.5 to 8.5 for drinking water (WHO, 2017), the acceptable discharge limits for industrial wastewater are typically between 6 and 9. Therefore, the outlet pH falls within permissible limits, indicating that the pH of the wastewater is effectively neutralized before being discharged.

The graph illustrates the trend of TDS levels at the inlet and outlet over time. The inlet TDS values frequently

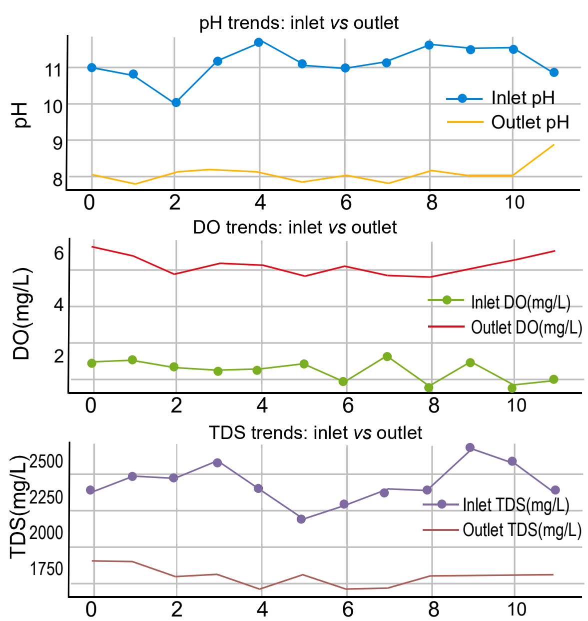

Fig. 6. Trends of pH, dissolved oxygen (DO) and total dissolved solids (TDS) at inlet *vs*. outlet.

Table 4. Dhaka export processing zone, Gonakbari, Ashulia, Savar, Dhaka-1349

Tested parameters						Remarks
Inlet			Outlet			
pH (6-9)	DO (4.5-8) mg/L	TDS (≤2100) mg/L	pH (6-9)	DO (4.5-8) mg/L	TDS (≤2100) mg/L	
11.0	1.9	2300	8.0	6.2	1800	OK
10.8	2.0	2400	7.8	5.8	1800	OK
10.0	1.7	2400	8.1	5.1	1700	OK
11.2	1.6	2500	8.2	5.5	1700	OK
11.7	1.6	2300	8.1	5.5	1600	OK
11.1	1.8	2100	7.8	5.1	1700	OK
11.0	1.2	2200	8.0	5.4	1600	OK
11.1	2.1	2300	7.8	5.1	1600	OK
11.6	1.0	2300	8.1	5.0	1700	OK
11.5	1.9	2600	8.0	5.3	1700	OK
11.5	1.0	2500	8.0	5.6	1700	OK
10.9	1.2	2300	8.9	6.0	1700	OK

exceed the permissible limit, peaking at 2600 mg/L, while the outlet TDS levels are consistently reduced to below 1800 mg/L, indicating the effectiveness of the wastewater treatment process.

In terms of dissolved oxygen (DO), the inlet values are alarmingly low, between 1.0 and 2.0 mg/L, which indicates oxygen-depleted water. According to general water quality guidelines, DO levels should be within the range of 4.5 to 8 mg/L to sustain aquatic life and ensure safe water quality (UNEP, 2004). After treatment, the DO levels rise to a healthier range of 5.0 to 6.2 mg/L, meeting the acceptable range, reflecting the successful oxygenation of the treated water.

For total dissolved solids (TDS), the inlet levels frequently exceed the permissible limit of 2100 mg/L, peaking at 2600 mg/L. WHO recommends a TDS limit of ≤1000 mg/L for drinking water, but for industrial wastewater discharge, the limit is generally around 2100 mg/L (WHO, 2011). Post-treatment, the TDS levels are consistently reduced to below 1800 mg/L, which demonstrates that the treatment process effectively removes excess dissolved solids, ensuring that the discharged water meets environmental standards.

Finally, the data suggests that the treatment system is functioning well to ensure that the discharged water adheres to environmental and health safety standards.

The graphical analysis of Fig. 7 and (Table 5) stated that pH, DO and TDS trends providing a clear visualization of the improvements in water quality from inlet to outlet after treatment. In terms of health impacts, while high TDS levels can introduce harmful contaminants, excessively low TDS (<50 mg/L) can also have negative effects. Water with very low TDS lacks essential minerals like Ca, Mg and K, leading to potential mineral deficiencies and electrolyte imbalances if consumed over long periods (WHO, 2017). Low TDS water also tends to taste bland and can become corrosive, leaching harmful metals such as copper and lead from pipes, further endangering health (UNEP 2004). Moreover,

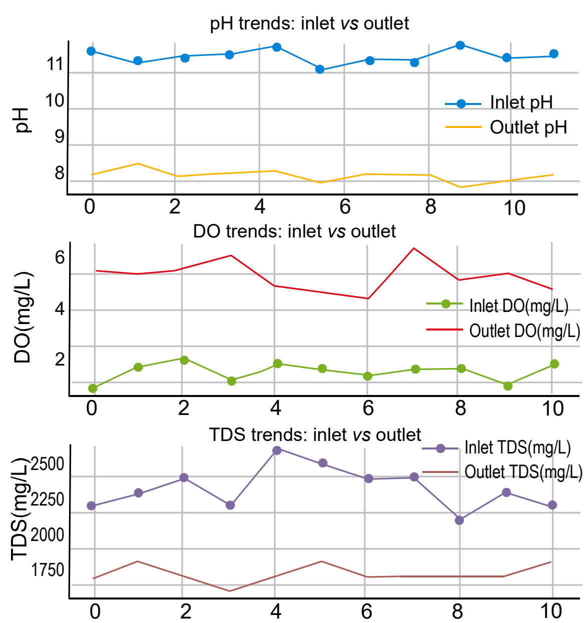

Fig. 7. Trends of pH, dissolved oxygen (DO) and total dissolved solids (TDS) at inlet *vs*. outlet.

Table 5. Dhaka export processing zone, Gonakbari, Ashulia, Savar, Dhaka-1349

Tested parameters						Remarks
Inlet			Outlet			
pH (6-9)	DO (4.5-8) mg/L	TDS (≤2100) mg/L	pH (6-9)	DO (4.5-8) mg/L	TDS (≤2100) mg/L	
11.3	0.9	2200	8.0	5.8	1700	OK
11.0	1.8	2300	8.3	5.7	1800	OK
11.1	2.1	2400	8.0	5.8	1700	OK
11.2	1.2	2200	8.1	6.4	1600	OK
11.4	1.9	2600	8.1	5.2	1700	OK
10.8	1.7	2500	7.8	4.9	1800	OK
11.0	1.4	2400	8.0	4.6	1700	OK
11.0	1.7	2400	8.0	6.8	1700	OK
11.4	1.7	2100	7.7	5.4	1700	OK
11.1	1.0	2300	7.8	5.7	1700	OK
11.2	1.9	2200	8.0	5.1	1800	OK

ecosystems depend on a certain mineral composition in water and excessively low TDS disrupts this balance, negatively affecting aquatic life. Therefore, both extremes of TDS high and low pose risks to human health and the environment. The water treatment process in this study is effectively managing these risks by bringing TDS and DO levels within acceptable ranges.

The graphical analysis of Fig. 8 and (Table 6) showed pH, DO and TDS trends provides a clear visualization of the improvements in water quality from inlet to outlet after treatment. For pH, the inlet values are significantly higher, ranging between 10.3 and 11.9, which exceed the WHO-recommended safe range of 6.5 to 8.5 for drinking water and 6.0 to 9.0 for industrial discharge (WHO, 2017). After treatment, the outlet pH levels stabilize between 8.0 and 8.3, showing that the water has been effectively neutralized, ensuring compliance with discharge standards. In the case of DO, the inlet levels are critically low, ranging between 1.4 and 2.4 mg/L, indicating poor oxygenation in the untreated water. WHO guidelines recommend maintaining DO levels between 4.5 and 8.0 mg/L for safe water discharge and to support aquatic ecosystems (UNEP 2004). Post-treatment, the outlet DO levels improve significantly, rising to 5.0-6.2 mg/L, which falls within the acceptable range, demonstrating successful oxygenation of the water. For TDS, the inlet levels frequently exceed the WHO's recommended limit of 2100 mg/L for treated wastewater, with peaks reaching up to 2500 mg/L. However, after treatment, the TDS levels decrease to below 2000 mg/L, reflecting the effective removal of dissolved solids (WHO, 2011). This reduction ensures that the treated water meets both environmental and health safety standards.

The trends in these graphs collectively show that the treatment process is successfully adjusting the water's pH, increasing DO levels and reducing TDS concentrations to meet WHO guidelines, making the water safer for both discharge and potential human interaction.

The graphical analysis of Fig. 9 and (Table 7) showed pH, DO and TDS reveals significant differences

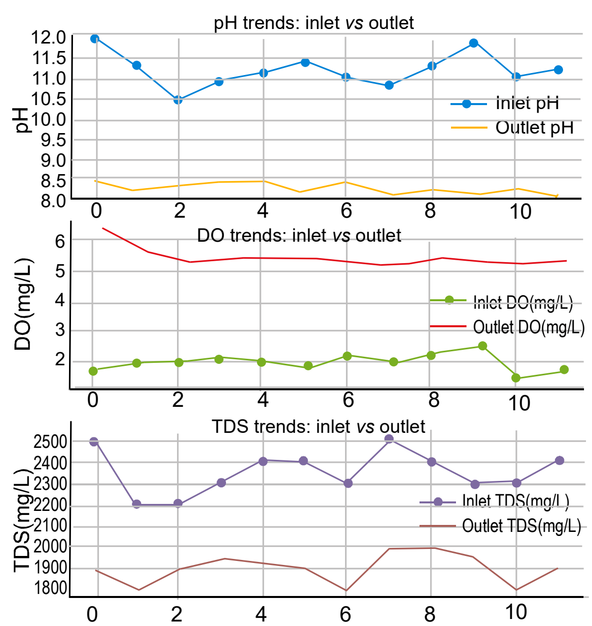

Fig. 8. Trends of pH, dissolved oxygen (DO) and total dissolved solids (TDS) at inlet *vs*. outlet.

Table 6. Dhaka export processing zone, Gonakbari, Ashulia, Savar, Dhaka-1349

Tested parameters						Remarks
Inlet			Outlet			
pH (6-9)	DO (4.5-8) mg/L	TDS (≤2100) mg/L	pH (6-9)	DO (4.5-8) mg/L	TDS (≤2100) mg/L	
11.9	1.7	2500	8.3	6.2	1900	OK
11.2	1.9	2200	8.1	5.5	1800	OK
10.3	1.9	2200	8.2	5.1	1900	OK
10.8	2.1	2300	8.3	5.2	1947	OK
11.0	2.0	2400	8.3	5.2	1940	OK
11.3	1.8	2400	8.1	5.2	1900	OK
10.9	2.1	2300	8.3	5.1	1800	OK
10.7	1.9	2500	8.0	5.0	1993	OK
11.2	2.2	2400	8.1	5.2	2000	OK
11.8	2.4	2300	8.0	5.1	1950	OK
10.9	1.4	2300	8.1	5.0	1800	OK
11.1	1.6	2400	8.0	5.1	1900	OK

between the inlet and outlet water quality. The inlet pH values, ranging from 11.5 to 11.8, indicate highly alkaline wastewater, which is effectively neutralized to between 8.1 and 8.3 after treatment, aligning with acceptable discharge limits (WHO, 2017). The DO levels at the inlet are critically low, between 0.9 and 1.2 mg/L, reflecting oxygen depletion. After treatment, DO levels improve to between 5.0 and 5.5 mg/L, enhancing the water's capacity to support aquatic life (UNEP 2004). However, the TDS levels remain a concern. Inlet TDS levels are excessively high, reaching up to 3600 mg/L, far surpassing the WHO-recommended limit of 2100 mg/L (WHO, 2011). Despite some reduction post-treatment, outlet TDS values remain elevated, ranging between 2870 and 2950 mg/L, indicating the need for enhanced filtration. The health impact of such high TDS levels can be severe, leading to kidney and cardio-vascular issues if consumed, while low DO can harm aquatic ecosystems. Even though the pH and DO levels show significant improvement post-treatment, the persistent high TDS signals the necessity for further improvements in wastewater filtration to meet health and environmental standards.

The graphical analysis of Fig. 10 and (Table 8) displayed pH, DO and TDS shows distinct differences between the inlet and outlet water quality after treatment. Inlet pH values range between 11.1 and 11.6, indicating highly alkaline water, while the outlet pH decreases to 7.9-8.1, bringing it within the acceptable discharge limits (6-9). The DO levels at the inlet are critically low, between 1.0 and 1.3 mg/L, signifying poor oxygenation, whereas the outlet DO improve to between 5.6 and 5.8 mg/L, aligning with acceptable standards (4.5-8 mg/L). However, TDS levels remain a concern, with inlet values between 2185 and 2510 mg/L and outlet TDS only slightly reduced to 2180-2393 mg/L, exceeding the WHO-recommended limit of 2100 mg/L.

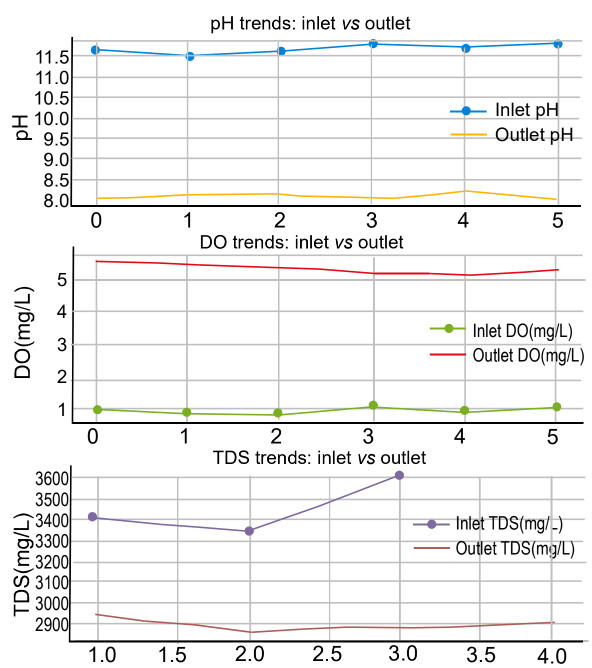

Fig. 9. Trends of pH, dissolved oxygen (DO) and total dissolved solids (TDS) trends at inlet *vs*. outlet.

Table 7. Dhaka export processing zone, Gonakbari, Ashulia, Savar, Dhaka-1349

Tested parameters						Remarks
Inlet			Outlet			
pH (6-9)	DO (4.5-8) mg/L	TDS (≤2100) mg/L	pH (6-9)	DO (4.5-8) mg/L	TDS (≤2100) mg/L	
11.6	1.1	--	8.1	5.5	--	OK
11.5	1.0	3400	8.2	5.4	2950	TDS value out of standard
11.6	0.90	3340	8.2	5.3	2870	TDS value out of standard
11.8	1.2	3600	8.1	5.1	2900	TDS value out of standard
11.7	1.0	--	8.3	5.1	2920	TDS value out of standard
11.8	1.2	--	8.1	5.2	--	OK

The graphical analysis of Fig. 11 and (Table 9) exhibited significant changes between the inlet and outlet water quality after treatment. The inlet pH levels, which range from 11.2 to 11.6, indicate highly alkaline wastewater. After treatment, the pH values drop to between 7.8 and 8.1, bringing the water within acceptable discharge limits, indicating successful pH neutralization. Dissolved oxygen levels at the inlet are critically low, ranging between 1.0 and 1.3 mg/L, signifying oxygen depletion in untreated water. Post-treatment, DO improves significantly to 5.9-6.1 mg/L, which is within the range necessary to support aquatic life. However, the total dissolved solids levels remain concerning. Inlet TDS values are high, between 2365 and 2510 mg/L, exceeding the WHO-recommended limit of 2100 mg/L. Although treatment reduces TDS to some extent, the outlet values still remain elevated between 2310 and 2610 mg/L, indicating the need for additional filtration to achieve acceptable TDS levels for environmental safety.

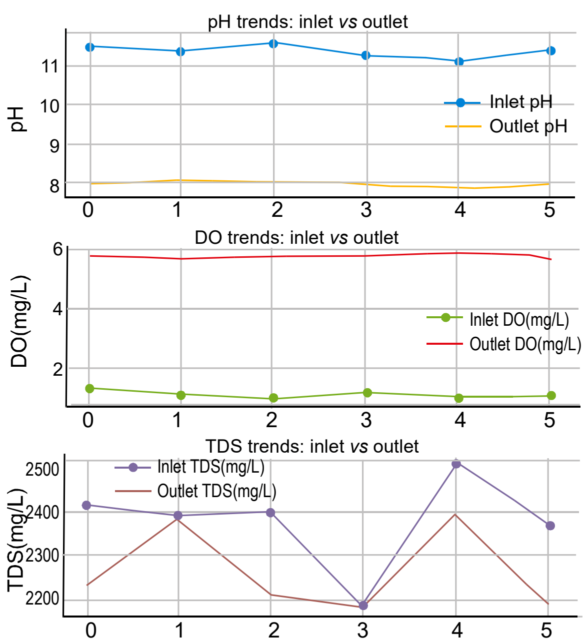

Fig. 10. Trends of pH, dissolved oxygen (DO) and total dissolved solids (TDS) at inlet *vs*. outlet.

Optimizing textile wastewater management for health and environmental sustainability. The discharge of textile industry wastewater containing high total dissolved solids (TDS), low dissolved oxygen (DO) and other pollutants poses significant risks to human health, ecosystems and agriculture. Elevated TDS levels can cause kidney damage, cardiovascular issues and affect the taste and potability of drinking water (Rahman *et al.*, 2018). Low DO levels at the inlet can stress aquatic life, causing hypoxia and disrupting the aquatic food web, with subsequent effects on human food resources (Hossain *et al.*, 2018). Persistent high TDS in outlet water further degrades water quality and harms ecosystems, making untreated discharges a major environmental concern (Setiadi *et al.*, 2006). While improvements in pH and DO levels are beneficial, the continued high TDS levels indicate a need for more effective treatment technologies (Aquino *et al.*, 2014). Furthermore, excessive DO levels, although typically beneficial, can cause negative impacts such as gas bubble disease in fish (Vargas *et al.*, 2009) and infrastructure corrosion (Christie, 2001), highlighting the complexity of achieving optimal water quality.

Industrial wastewater, particularly from textile factories,

Table 8. Dhaka export processing zone, Gonakbari, Ashulia, Savar, Dhaka-1349

Tested parameters						Remarks
Inlet			Outlet			
pH (6-9)	DO (4.5-8) mg/L	TDS (≤2100) mg/L	pH (6-9)	DO (4.5-8) mg/L	TDS (≤2100) mg/L	
11.5	1.3	2413	8.0	5.7	2230	TDS value out of standard
11.4	1.1	2390	8.1	5.6	2380	TDS value out of standard
11.6	1.0	2397	8.0	5.7	2210	TDS value out of standard
11.3	1.2	2185	8.0	5.7	2180	TDS value out of standard
11.1	1.0	2510	7.9	5.8	2393	TDS value out of standard
11.4	1.1	2370	8.0	5.6	2190	TDS value out of standard

is associated with numerous health issues, including anemia, low blood platelets, headaches, cancer risks and skin diseases. The discharge of untreated effluent into rivers like the Buriganga, Turag and Shitalakkhya has caused severe contamination, severely affecting aquatic life and public health. Textile effluents are highly toxic and carcinogenic due to the presence of synthetic dyes, heavy metal salts and inorganic compounds (Islam *et al*., 2023; Kabir *et al*., 2019; Islam and Mostafa, 2019; Hasan *et al*., 2014). These pollutants also leach into agricultural lands, reducing soil fertility and diminishing crop yields, which, in turn, threaten the livelihoods of farmers (Islam, 2022). The discharge of untreated or inadequately treated wastewater from the textile industry poses a severe threat to public health, ecosystems and agricultural sustainability (Saravanakumar *et al*., 2022).

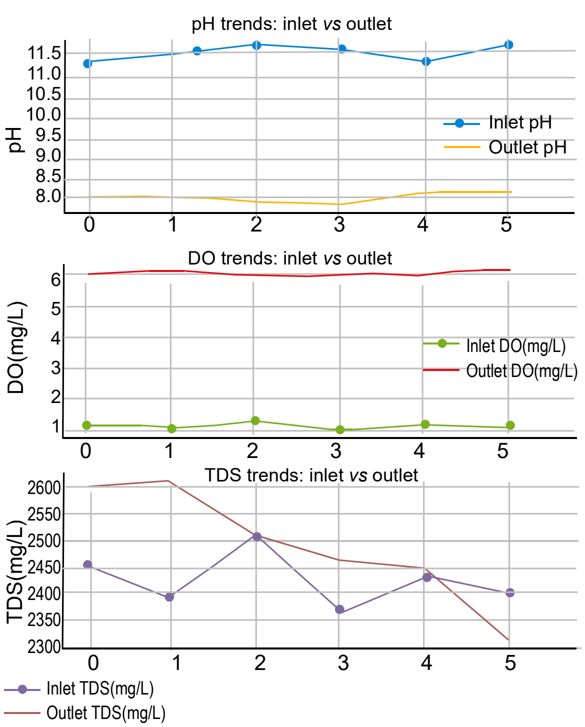

Fig. 11. Trends of pH, dissolved oxygen (DO) and total dissolved solids (TDS) at inlet *vs*. outlet.

This wastewater is often characterized by high TDS, low DO and elevated levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD), all of which contribute to environmental degradation and long-term health concerns. High TDS levels, often caused by dissolved salts, heavy metals and chemicals used in textile processing, degrade water quality and render it unsuitable for consumption. Chronic exposure to high TDS levels in drinking water has been linked to kidney disease, cardiovascular problems and metabolic disorders. Additionally, heavy metals such as lead, mercury and chromium, commonly found in textile wastewater, accumulate in the body over time, increasing the risk of neurological disorders, cancer and organ damage. Furthermore, TDS contamination in irrigation water leads to salt accumulation in the soil, reducing its fertility, stunting plant growth and diminishing agricultural yields, ultimately threatening food security and the livelihoods of farmers.

Table 9. Dhaka export processing zone, Gonakbari, Ashulia, Savar, Dhaka- 1349

Tested parameters						Remarks
Inlet			Outlet			
pH (6-9)	DO (4.5-8) mg/L	TDS (≤2100) mg/L	pH (6-9)	DO (4.5-8) mg/L	TDS (≤2100) mg/L	
11.2	1.2	2453	8.0	6.0	2600	TDS value out of standard
11.4	1.1	2390	8.0	6.1	2610	TDS value out of standard
11.6	1.3	2510	7.9	5.9	2510	TDS value out of standard
11.5	1.0	2365	7.8	6.0	2460	TDS value out of standard
11.2	1.2	2430	8.1	6.0	2443	TDS value out of standard
11.6	1.1	2400	8.1	6.1	2310	TDS value out of standard

Low DO levels in wastewater exacerbate environmental problems, particularly in aquatic ecosystems. DO is essential for aquatic organisms to survive, its depletion leads to hypoxic conditions, which cause fish kills and disrupt the balance of aquatic food chains. This degradation not only affects biodiversity but also reduces the availability of fish as a food source, indirectly impacting human nutrition and livelihoods dependent on fisheries. Moreover, hypoxia leads to the growth of harmful anaerobic bacteria which can further deteriorate water quality and contribute to the spread of waterborne diseases (Garg *et al*., 2022).

Elevated BOD and COD levels in textile wastewater indicate high concentrations of organic and chemical pollutants, which accelerate oxygen depletion when discharged into natural water bodies. This results in the breakdown of aquatic ecosystems, loss of biodiversity and increased water toxicity (Saravanakumar *et al*., 2022). In agricultural settings, irrigation with high-BOD and high-COD wastewater harms soil microbial communities, reduces nutrient availability and decreases crop productivity. The contamination of rivers such as the Buriganga, Turag and Shitalakkhya in Bangladesh serves as a stark example of how textile effluents degrade freshwater resources, rendering them unsuitable for human consumption and agricultural use.

While some improvements in wastewater treatment have been observed, persistent high TDS levels remain a significant challenge. Although the use of effluent treatment plants (ETPs) has helped to reduce organic load and improve pH and DO levels, their efficiency in removing dissolved solids and heavy metals remains inadequate. The continued discharge of untreated or partially treated textile wastewater underscores the urgent need for advanced treatment technologies such as reverse osmosis (RO), ion exchange and activated carbon filtration. Additionally, the adoption of zero liquid discharge (ZLD) systems which eliminate wastewater discharge by recycling and reusing treated water, presents a viable long-term solution to mitigate environmental and health risks.

This research highlights critical gaps in Bangladesh's textile wastewater management strategies and underscores the need for regulatory enforcement, continuous monitoring and technological advancements. The implementation of Z-score analysis and other monitoring techniques can help detect non-compliance with environmental standards, allowing authorities to take corrective measures before contamination reaches critical levels. By integrating sustainable wastewater treatment solutions and adhering to Bangladesh's environmental conservation rules, the textile industry can significantly reduce its ecological footprint, ensuring safer water resources, healthier communities and more resilient agricultural systems.

Mitigating strategies for textile industry wastewater contaminants. Effective wastewater management in the textile industry requires targeted approaches to reduce contaminants such as total dissolved solids (TDS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), total suspended solids (TSS) and carbon dioxide (CO_2).

High TDS levels, caused by dissolved salts, heavy metals and textile chemicals, can be mitigated using reverse osmosis (RO), ion exchange, electrodialysis (ED), zero liquid discharge (ZLD) systems, chemical precipitation and evaporation-crystallization. Additionally, nano-filtration (NF) is used to selectively remove dissolved salts, while preserving essential minerals and forward osmosis (FO) offers an energy-efficient alternative for TDS reduction.

For high BOD levels, strategies such as the activated sludge process, aerated lagoons, trickling filters, constructed wetlands and chemical oxidation (using ozone or hydrogen peroxide) help break down organic pollutants and improve water quality. COD reduction requires advanced oxidation processes (AOPs), electro-coagulation, fenton's process, granular activated carbon (GAC) filtration and membrane bioreactors (MBRs), which effectively remove non-biodegradable and complex organic pollutants. Wet air oxidation (WAO) is another promising technique that decomposes toxic organic compounds at high temperatures and pressures.

Maintaining optimal DO levels is crucial, as low DO can cause aquatic hypoxia, while excessive DO leads to infrastructure corrosion and fish diseases. Aeration techniques such as surface aerators, diffused aeration systems, cascade aerators and oxygen injection systems help maintain proper DO levels, while reducing organic loads prevents oxygen depletion.

High TSS levels contribute to turbidity and sludge accumulation, which can be controlled through sedimentation tanks, coagulation-flocculation (using alum or ferric chloride), sand and membrane filtration, dissolved air flotation (DAF) and sludge dewatering techniques like centrifuges, filter presses and drying beds. Additional methods such as ultrafiltration (UF), microfiltration (MF) and electrochemical treatment provide enhanced solid-liquid separation and pollutant removal.

Mitigating CO_2 in textile wastewater treatment. Textile wastewater treatment processes contribute to CO_2 emissions, primarily from energy-intensive treatment methods and the biological degradation of organic pollutants. Effective mitigation strategies align with several sustainable development goals (SDGs), particularly SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 9 (industry, innovation and infrastructure), SDG 12 (responsible consumption and production) and SDG 13 (climate action).

To reduce CO_2 emissions, carbon capture and storage (CCS) techniques can be integrated into treatment facilities, using adsorption-based systems such as activated carbon, biochar or amine-based scrubbers to trap CO_2 before release (SDG 9, SDG 13). Algae-based CO_2 sequestration offers a sustainable approach by utilizing microalgae to absorb CO_2, while simultaneously removing nutrients like nitrogen and phosphorus from wastewater, promoting a circular economy (SDG 6, SDG 12). Anaerobic digestion with biogas recovery not only converts organic pollutants into methane for energy production but also reduces CO_2 emissions, supporting cleaner energy alternatives (SDG 7, SDG 12) (WHO/UNICEF, 2021).

Integrating renewable energy sources such as solar, wind or hydroelectric power into wastewater treatment facilities significantly cuts CO_2 emissions by reducing reliance on fossil fuels (SDG 7, SDG 13). Additionally, electrochemical CO_2 reduction presents an emerging method to convert CO_2 into useful chemicals like formic acid or methanol for industrial reuse, promoting sustainable industry practices (SDG 9, SDG 12).

By implementing these mitigation strategies, the textile industry can lower its carbon footprint, enhance wastewater treatment efficiency and contribute to global climate action efforts, ultimately ensuring a more sustainable and environmentally responsible approach to textile production and wastewater management.

Recommendations and key performance indicators (KPIs) for sustainable wastewater management in Bangladesh's textile industry. ***Recommendations for wastewater management.*** For the sake of substantially improving wastewater management in Bangladesh's textile industry, a multifaceted approach is required. This should combine innovative technologies, strict regulatory enforcement and the widespread adoption of sustainable practices. To effectively reduce total dissolved solids (TDS), heavy metals and persistent organic pollutants, specific advanced treatment technologies must be implemented. These include membrane bioreactors (MBR) for biological treatment, nanofiltration (NF) for dye and heavy metal removal, reverse osmosis (RO) for TDS reduction and ultimately, zero liquid discharge (ZLD) systems for maximum water recovery. A rigorous cost-benefit analysis should precede the introduction of these technologies, taking into account the economic realities of Bangladesh's major and small-to-medium enterprises (SMEs). Consistent, standardized monitoring of major pollutants (TDS, BOD, COD, heavy metals and particular dyes) utilizing Z-score analysis at clearly specified frequencies and responsibilities is critical for detecting noncompliance early and taking corrective action immediately. In order to minimize pollutant loads at the source, the industry should switch to certified eco-friendly dyes, such as those that meet OEKO-TEX standards and provide comprehensive, ongoing training for personnel at all levels, focusing on best practices in chemical handling, process optimization and wastewater management. It is critical to strengthen regulatory monitoring by enforcing existing laws and developing new, context-specific standards, in conjunction with incentive-based treated water recycling programs. Investment in R&D, focusing on cost-effective, locally adapted technology, while taking into consideration Bangladesh's current infrastructure and worker education levels, will stimulate innovation and create long-term sustainability across the sector. In addition to, community engagement and stakeholder participation must be incorporated into planning and execution to ensure societal acceptance and long-term success. Furthermore, a defined long-term monitoring mechanism and repercussions for failures must be developed.

Key performance indicators (KPIs). A thorough set of key performance indicators (KPIs) is designed to rigorously assess progress and assure compliance with regulatory requirements and sustainability objectives. This technology employs real-time monitoring and data integration for critical water quality metrics, shifting from static ECR 1997 compliance to dynamic criteria depending on local ecosystem health. Statistical process control (SPC) tools, such as Z-score analysis and control charts are used to discover trends and improve treatment procedures. Pollutant-specific reduction targets are developed based on baseline research and ecological risk assessments, as well as metrics for water reuse efficiency (WRE), energy consumption per unit of treated wastewater (ECU) and sludge valorization index (SVI). Chemical footprint reduction is quantified and the adoption rate and efficiency of sophisticated treatment methods, including their optimization in the context of Bangladesh are monitored. The training effectiveness index (TEI) assesses the effectiveness of employee training and knowledge transfer platforms are built. To drive innovation, measures like as R&D investment, publication output and collaboration are monitored. Instead of simple percentage reductions, precise pollutant reductions will be determined by local environmental sensitivity. Instead of an 80% TDS reduction, TDS will be decreased to a level considered safe for local aquatic life. Instead of a 90% reduction in BOD and COD, the levels will be adjusted so as to maintain DO levels between 4.5-8 mg/L. Z-score analysis and other SPC methods will be utilized to identify pollutant outliers and minimize non-compliant pollutants, with an emphasis on prediction and prevention. Annual training will incorporate TEI measures to guarantee employee readiness. Treated wastewater reuse will be measured using WRE, with a target reuse rate of 75%, as well as an economic and environmental cost-benefit analysis. ATTAR will track the uptake of modern treatment technologies, as well as their efficiency. Finally, all acquired data, while following security rules, will be made available to researchers and the general public, allowing for transparent and data-driven changes. Furthermore, an economic impact assessment system must be integrated to track each KPI's cost-effectiveness and influence on industrial competitiveness. Long-term ecological monitoring should be used to assess the long-term sustainability benefits of methods that have been adopted. The methodology should also include a social impact assessment that evaluates the implications on local communities, such as public health and resource availability.

Finally, a clear method for frequent evaluation and adaptation of KPIs in response to emerging research and technological improvements is required to ensure the framework's relevance and effectiveness. A detailed plan for long-term monitoring, as well as repercussions for failures, should be devised to build a measurable foundation for true sustainable growth and environmental safety in the textile industry.

Conclusion

The analysis of wastewater treatment in Bangladesh's textile industry highlights the vital role of effluent treatment plants (ETPs), while underscoring ongoing challenges, particularly with managing total dissolved solids (TDS). ETPs effectively improve water quality by stabilizing pH levels, increasing dissolved oxygen (DO) and reducing organic pollutants such as biochemical oxygen demand (BOD) and chemical oxygen demand (COD). These improvements contribute to healthier ecosystems and partial compliance with the environment conservation rules (ECR) 1997 for parameters like pH, DO, chloride and manganese.

However, persistent high TDS levels remain a significant concern. Elevated TDS concentrations pose risks to soil health, aquatic ecosystems and public health due to bioaccumulation of metals and other pollutants. This calls for advanced treatment technologies, such as zero liquid discharge (ZLD) systems and enhanced filtration techniques, to address these issues effectively. Furthermore, continuous monitoring through tools like Z-score analysis is essential to detect non-compliance early and drive continuous improvements.

While ETPs in Dhaka's export processing zone show promise in stabilizing pH levels, increasing DO and reducing organic pollutants, the persistent high TDS concentrations highlight the need for more advanced solutions. This research also points to gaps in the operational efficiency of ETPs, particularly regarding TDS, emphasizing the need for comprehensive evaluations and the integration of innovative treatment technologies. Strengthening regulatory oversight, promoting eco-friendly dyes and improving personnel training are also critical steps for enhancing wastewater management.

Even though ETPs play a crucial role in managing textile wastewater, more efficient and sustainable treatment technologies are necessary to meet regulatory standards and protect the environment. By aligning policies with industry needs, improving treatment processes and establishing measurable key performance indicators (KPIs), the textile industry can reduce its environmental impact and move toward more sustainable practices.

Conflict of Interest. The authors declare that they have no conflict of interest.

References

Akhtar, S., Fatima, R., Soomro, Z.A., Hussain, M., Ahmad, S.R., Ramzan, H.S. 2019. Bacteriological quality assessment of water supply schemes (WSS) of Mianwali, Punjab, Pakistan. *Environmental Earth Sciences*, **78:** 1-13. DOI: 10.1007/s12665-019-8455-1

APHA, E.W., Rice, R.B. Baird, A.D., Eaton, L.S. Clesceri. 2012. Standard methods for the examination of water and wastewater, 1496 pp. American Public Health Association (APHA), American Water Works Association (AWWA), Water Environment Federation (WEF), Washington, D.C., USA.

Aquino, J.M., Rocha-Filho, R.C., Ruotolo, L.A., Bocchi, N., Biaggio, S.R. 2014. Electrochemical degradation of a real textile wastewater using β-PbO_2 and DSA® anodes. *Chemical Engineering Journal*, **251:** 138-145. https://doi.org/10.1016/j.cej.2014.04.056

Baly, H.A. 2022. Textile dyeing effluents and its impact on environment. Textile Today. Retrieved January 3, 2022 from https://www.textiletoday.com.bd/textile-dyeing-effluents-and-its-impact-on-environment.

Begum, H.A., Haque, A.K.M.M., Islam, D., Hasan, M.M., Ahmed, S., Razzak, M., Khan, R.A. 2020. Analysis of the adsorption of toxic chromium (VI) by untreated and chitosan-treated banana and areca fibre. *Journal of Textile Science and Technology*, **6:** 81-106. DOI: 10.4236/jtst.2020.62007

Bhatia, S.C. 2017. *Pollution Control in Textile Industry*, pp. 342, WPI Publishing, New York, USA. https://doi.org/10.1201/9781315148588

Christie, R. 2007. *Colour Chemistry*, 218 pp., Royal Society of Chemistry, Cambridge, UK. https://doi.org/10.1039/9781847550590

Copaciu, F., Opris, O., Coman, V., Ristoiu, D., Niinemets, Ü., Copolovici, L. 2013. Diffuse water pollution by anthraquinone and azo dyes in the environment importantly alters foliage volatiles, carotenoids and physiology in wheat (*Triticum aestivum*). *Water, Air and Soil Pollution*, **224:** 1478. https://doi.org/10.1007/s11270-013-1478-0

Department of Environment (DoE). 2008. *Guide for Assessment of Effluent Treatment Plants*. Ministry of Environment and Forest, Bangladesh.

Din, I.U., Muhammad, S., Rehman, I.U. 2023. Groundwater quality assessment for drinking and irrigation purposes in the Hangu District, Pakistan. *Journal of Food Composition and Analysis*, **115:** 104919. https://doi.org/10.1016/j.jfca.2022.104919

Dutta, S., Adhikary, S., Bhattacharya, S., Roy, D., Chatterjee, S., Chakraborty, A., Banerjee, D., Ganguly, A., Nanda, S., Rajak, P. 2024. Contamination of textile dyes in the aquatic environment: adverse impacts on aquatic ecosystems and human health and its management using bioremediation. *Journal of Environmental Management*, **353:** 27, 120103. https://doi.org/10.1016/j.jenvman.2024.120103

ECR, 1997. Discharge into surface water: performance evaluation of zero liquid discharge-effluent treatment plants (ZLD-ETPs) in textile industries of Bangladesh, 10 pp., Publisher/Institution, Bangladesh.

Garg, S., Chowdhury, Z.Z., Faisal, A.N.M., Rumjit, N.P., Thomas, P. 2022. Impact of industrial wastewater on environment and human health. In: *Advanced Industrial Wastewater Treatment and Reclamation of Water*, Roy, S., Garg, A., Garg, S., Tran, T.A. (eds.), pp. 197-209, Springer, Cham, Switzerland. https://doi.org/10.1007/978-3-030-83811-9_10

Hassan, M.M., Carr, C.M. 2018. A critical review on recent advancements of the removal of reactive dyes from dyehouse effluent by ion-exchange adsorbents. *Chemosphere*, **209:** 201-219. https://doi.org/10.1016/j.chemosphere.2018.06.105

Hasan, M.M., Hossain, M.B., Azim, A.Y.M.A. 2014. Application of purified curcumin as natural dye on cotton and polyester. *International Journal of Engineering and Technology*, **14:** 17-23.

Hossain, L., Sarker, S.K., Khan, M.S. 2018. Evaluation of present and future wastewater impacts of textile dyeing industries in Bangladesh. *Environmental Development*, **26:** 23-33. https://doi.org/10.1016/j.envdev.2018.03.005

Imran, M., Crowley, D.E., Khalid, A., Hussain, S., Mumtaz, M.W., Arshad, M. 2015. Microbial biotechnology for decolourization of textile wastewaters. *Reviews in Environmental Science and Biotechnology*, **14:** 73-92. https://doi.org/10.1007/s11157-014-9342-9

Islam, M.R., Islam, M.S., Akter, J., Sultana, T. 2023. The studies of environmental load and consequences of leather industrial effluents in Bangladesh. *Journal of Environmental Impact and Management Policy*, **3:** 1-14. https://doi.org/10.55529/jeimp.31.1.14

Islam, T. 2022. Health concerns of textile workers and associated community. *SAGE Open*, **59:** e00469580221088626. https://doi.org/10.1177/00469580221088626

Islam, T., Repon, M.R., Islam, T., Sarwar, Z., Rahman, M.M. 2022. Impact of textile dyes on health and ecosystem: a review of structure, causes and potential solutions. *Environmental Science and Pollution Research*, **30:** 9207-9242. https://doi.org/10.1007/s11356-022-24398-3

Islam, M.R., Mostafa, M.G. 2020. Characterization of textile dyeing effluent and its treatment using polyaluminum chloride. *Applied Water Science*, **10:** 119. https://doi.org/10.1007/s13201-020-01204-4

Islam, M.R., Mostafa, M.G. 2019. Textile dyeing effluents and environmental concerns – a review. *Journal of Environmental Science and Natural Resources*, **11:** 131-140. DOI: 10.3329/jesnr.v11i1-2.43380

Ito, T., Adachi, Y., Yamanashi, Y., Shimada, Y. 2016. Long–term natural remediation process in textile dye–polluted river sediment driven by bacterial community changes. *Water Research*, **100:** 458-465. https://doi.org/10.1016/j.watres. 2016.05.052

Kabir, S.M., Hasan, M., Uddin, M. 2019. A novel approach to dye polyethylene terephthalate (PET) fabric in supercritical carbon dioxide with natural curcuminoid dyes. *Fibres and Textiles in Eastern Europe*, **27:** 65-70. DOI: 10.5604/01.3001.0013.0744

Kamal, R.S.B. 2016. The Bangladeshi RMG sector's impact on the environment. Dhaka Tribune. Retrieved September 3, 2024, from https://www.dhakatribune.com/magazine/weekend-tribune/298/awareness-required-for-effluent-treatment-plants

Khatri, J., Nidheesh, P.V., Singh, T.A., Kumar, M.S. 2018. Advanced oxidation processes based on zero-valent aluminium for treating textile wastewater. *Chemical Engineering Journal*, **348:** 67-73. https://doi.org/10.1016/j.cej.2018.04.173

Kingsley Group, 2024. Sustainable solutions: how ETP plants are revolutionizing the textile industry in Bangladesh. Retrieved October 27, 2024, from https://kingsleygroup.co/blogs/sustainable-solutions-how-etp-plants-are-revolutionizing-the-textile-industry-in-bangladesh

Mahapatra, N.N. 2016. *Textile Dyes*, 230 pp., WPI Publishing, New York, USA. https://doi.org/10.1201/b21336

Mansouri, A., Ait Aghazzaf, A., Draoui, K. 2025. Characterization of Moroccan raw and modified clay and its application in removal of methyl orange dye. *International Journal of Chemical Kinetics*, **57:** 297-314, https://doi.org/10.1002/kin.21777

Mapanda, F., Mangwayana, E.N., Nyamangara, J., Giller, K.E. 2005. The effect of long-term irrigation using wastewater on heavy metal contents of soils under vegetables in Harare, Zimbabwe. *Agriculture, Ecosystems and Environment*, **107:** 151-165. https://doi.org/10.1016/j.agee.2004.11.005

Moloi, M., Ogbeide, O., Otomo, P.V. 2020. Probabilistic health risk assessment of heavy metals at wastewater discharge points within the Vaal River Basin, South Africa. *International Journal of Hygiene and Environmental Health*, **224:** 113421. DOI: 10.1016/

j.ijheh.2019.113421
Murei, A., Kamika, I., Momba, M.N.B. 2024. Selection of a diagnostic tool for microbial water quality monitoring and management of faecal contamination of water sources in rural communities. *Science of the Total Environment*, **906:** 167484. doi: 10.1016/j.scitotenv.2023.167484. Epub 2023 Oct 5. PMID: 37804981
Muthu, S.S. 2017. *Sustainability in the Textile Industry* vol. **1,** pp. 200, Springer, Singapore. https://doi.org/10.1007/978-981-10-2639-3
Newman, M.C. 2019. *Fundamentals of Ecotoxicology: the Science of Pollution*, vol. **1,** pp. 708, 5th eds., CRC Press, Boca Raton, FL, USA. https://doi.org/10.1201/9781351133999
Nwodo, B.C., Mohammed, A.D., Mohammed, A.D., Abisoye, O., Abisoye, O., Bashir, S.A. 2021. Outlier detection in multivariate time series data using a fusion of K-medoid, standardized Euclidean distance and Z-score. In: *Information and Communication Technology and Applications, 3rd International Conference, ICTA 2020*, Minna, Nigeria, November 24-27, 2020, Revised Selected Papers (pp. 317-329). Springer. https://doi.org/10.1007/978-3-030-69143-1_21
Ondieki, J.K., Akunga, D., Warutere, P., Kenyanya, O. 2021. Bacteriological and physico-chemical quality of household drinking water in Kisii Town, Kisii County, Kenya. *Heliyon*, **7:** e06937. https://doi.org/10.1016/j.heliyon.2021.e06937
Orts, F., del Río, A.I., Molina, J., Bonastre, J., Cases, F. 2018. Electrochemical treatment of real textile wastewater: trichromy procion hexl®. *Journal of Electroanalytical Chemistry*, **808:** 387-394. https://doi.org/10.1016/j.jelechem.2017.06.051
Pérez-González, A., Urtiaga, A.M., Ibáñez, R., Ortiz, I. 2012. State of the art and review on the treatment technologies of water reverse osmosis concentrates. *Water Research*, **46:** 2, 267-283. https://doi.org/10.1016/j.watres.2011.10.046
Rahman, M.H., Muzib, S., Chaity, R.A. 2018. Ready-made garments of Bangladesh: an overview. *Barishal University Journal Part 1*, **5:** 59-122.
Rawat, D., Mishra, V., Sharma, R.S. 2016. Detoxification of azo dyes in the context of environmental processes. *Chemosphere*, **155:** 591-605. https://doi.org/10.1016/j.chemosphere.2016.04.068
Rehman, K., Shahzad, T., Sahar, A., Hussain, S., Mahmood, F., Siddique, M.H., Siddique, M.A., Rashid, M.I. 2018. Effect of reactive black 5 azo dye on soil processes related to C and N cycling. *PeerJ*, **6:** e4802. https://doi.org/10.7717/peerj.4802
Saravanakumar, K., De Silva, S., Santosh, S.S., Sathiyaseelan, A., Ganeshalingam, A., Jamla, M., Narayanan, S., A., Veeraraghavan, V.P., Ali, D.M., Lee, J., Thiripuranathar, G., Wang, M.H. 2022. Impact of industrial effluents on the environment and human health and their remediation using MOFs-based hybrid membrane filtration techniques. *Chemosphere*, **307:** 135593. https://doi.org/10.1016/j.chemosphere.2022.135593
Setiadi, T., Andriani, Y., Erlania, M. 2006. Treatment of textile wastewater by a combination of anaerobic and aerobic processes: a denim processing plant case. In: *Southeast Asian Water Environment 1: Selected papers from the First International Symposium on Southeast Asian Water Environment (Biodiversity and Water Environment)*, pp. 159-166, Ohgaki, S., Fukushi, K., Katayama, H., Takizawa, S., Polprasert, C. (eds.), IWA Publishing, Bangkok, Thailand.
Shamey, R., Zhao, X. 2014. *Modelling, Simulation and Control of the Dyeing Process*, 300 pp., Woodhead Publishing, Cambridge, UK. https://www.sciencedirect.com/book/9780857091338/modelling-simulation-and-control-of-the-dyeing-process#book-info
Snyman, H.G., Van Niekerk, A.M., Rajasakran, N. 2006. *Sustainable Wastewater Treatment–What has Gone Wrong and How Do We Get Back on Track*, 10 pp., May, Durban. https://www.researchgate.net/publication/228685969_Sustainable_wastewater_treatment-what_has_gone_wrong_and_how_do_we_get_back_on_track
Textile School. 2024. Effluent treatment process in garment manufacturing. Textile School. Retrieved September 3, 2024 from https://www.textileschool.com/7767/effluent-treatment-process-in-garment-manufacturing/2/
The Daily Star. 2024. Bangladesh's garment industry: future growth in a changing world. Retrived February 15, 2024 from https://www. thedailystar.net/anniversary-supplement-2024/ bangladesh-the-world-stage/news/bangladeshs-garment-industry-future-growth-changing-world-3543371
United Nations Environment Programme, 2004. Water quality for ecosystem and human health. https://www.unep.org/resources/report/water-quality-ecosystem-and-human-health
Vargas, A.M.M., Paulino, A.T., Nozaki, J. 2009. Effects

of daily nickel intake on the bio-accumulation, body weight and length in tilapia (*Oreochromis niloticus*). *Toxicological and Environmental Chemistry*, **91:** 751-759. https://doi.org/10.1080/02772240802524671

Wardman, R.H. 2017. *An Introduction to Textile Coloration: Principles and Practice*, 384 pp., Wiley, Chichester, UK. https://www.wiley.com/en-us/An+Introduction+to+Textile+Coloration%3A+Principles+and+Practice-p-9781119121565

Waterman Engineers Australia, 2024. Textile dyes: dyeing process and environmental impacts. Waterman Engineers Australia. Retrieved October 27, 2024, from https://watermanaustralia.com/textile-dyes-dying-process-and-environmental-impacts

WHO/UNICEF, 2021. Progress on Household Drinking Water, Sanitation and Hygiene 2000-2020: Five Years into the SDGs. *World Health Organization.* https:// www.who.int/publications/i/item/9789240030848

WHO/UNICEF, 2014. Progress on Drinking Water and Sanitation: 2014 Update. *World Health Organization.* https://data.unicef.org/resources/progress-on-drinking-water-and-sanitation-2014-report/

WHO, 2017. Guidelines for Drinking-water Quality. https://www.who.int/publications/i/item/9789241549950.

WHO, 2011. Guidelines for Drinking-water Quality. https://www.who.int/publications/i/item/9789241548151