The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES
21(3): 710-718, 2026
www.thebioscan.com

Physicochemical Assessment and Treatment Efficiency of a Textile Effluent Treatment Plant in Bhiwani, Haryana, India

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DOI: https://doi.org/10.63001/tbs.2026.v21.i03.pp710-718

KEYWORDS
Textile wastewater; Effluent treatment plant; Physicochemical characterization; Wastewater treatment; CPCB standards; BOD; COD; Heavy metals.

Received on: 15-06-2026

Revised on: 26-07-2026

Accepted on: 21-08-2026

Published on: 22-08-2026

Abstract

Background- Textile processing industries generate large volumes of wastewater containing organic pollutants, suspended and dissolved solids, nutrients, and trace metals. Effective treatment of these effluents is essential to minimize environmental impacts and comply with regulatory discharge standards. **Objective:** To evaluate the performance of an effluent treatment plant (ETP) Methods: A case study was undertaken on a textile processing unit in Bhiwani, Haryana, by comparing untreated influent and treated effluent collected on 12 February 2026. APHA method was performed on collecting samples, including regressions, PCA, and correlations of variables on SPSS. Wastewater samples were analysed in triplicate for eighteen physicochemical parameters, including pH, temperature, total dissolved solids (TDS), total suspended solids (TSS), hardness, alkalinity, chloride, sulfate, phosphate, colour, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and selected trace metals. **Findings**: Treatment substantially improved wastewater quality across nearly all parameters. BOD decreased from 268.7 to 6.1 mg/L (97.7% removal), COD from 688.7 to 33.7 mg/L (95.1% removal), and TSS by more than 99%. Concentrations of all regulated parameters in the treated effluent complied with the discharge standards prescribed by the Central Pollution Control Board (CPCB) under Schedule VI of the Environment (Protection) Rules, 1986, as implemented by the Haryana State Pollution Control Board (HSPCB). In contrast, TDS, chloride, and sulfate showed comparatively smaller reductions, reflecting the limited ability of conventional treatment processes to remove dissolved ions. **Novelty and applications:** This study reviewed the ETP operated efficiency during the study period and verified the treated effluent's suitability for discharge under the applicable regulatory standards, while also identifying dissolved solids as an area for further process improvement.

1. INTRODUCTION

The textile industry is one of the largest industrial consumers of water in India and consequently produces considerable volumes of wastewater. Approximately 100–200 litres of water are required to process one kilogram of fabric, while textile manufacturing is estimated to contribute nearly 20% of global industrial water pollution (Rahman & Tabassum, 2023). Wastewater is produced during various processing stages including desizing, scouring, bleaching, mercerising, dyeing, printing, and finishing. These effluents mainly contain dissolved and suspended solids, residual dyes, surfactants, organic matter, salts, and occasionally trace metals (Bhatia et al., 2018; Kehinde & Aziz, 2014; Öztürk et al., 2009; Zaharia & Suteu, 2012). Of the approximately 10,000 dyes used worldwide, an estimated 10–15% may enter the environment during dyeing and finishing operations (Öztürk et al., 2009). If discharged without proper treatment, textile effluents can reduce dissolved oxygen levels, restrict light penetration because of persistent colour, disturb aquatic ecosystems, and contaminate surface water, groundwater, and agricultural soils (Collivignarelli et al., 2019; Islam & Mostafa, 2020; Yaseen & Scholz, 2018).The ongoing expansion of textile manufacturing has made effective wastewater management an important environmental and regulatory concern. Modern effluent treatment plants (ETPs) are designed to remove organic pollutants, suspended solids, nutrients, and toxic substances. However, their treatment efficiency is affected by the wastewater characteristics, the treatment configuration, operating conditions, and the level of regular maintenance (Singh et al., 2008). Regular monitoring of ETP performance is therefore necessary to ensure fulfillment with discharge standards and to identify treatment stages that need improvement (Madan et al., 2024).Haryana has a well-established textile sector with several important industrial clusters (Chahal et al., 2025). Bhiwani, supported by regional cotton production and continuing industrial development, has emerged as a growing centre for textile processing. This expansion has increased the generation of highly coloured effluents containing substantial amounts of organic matter and dissolved salts, creating concerns about the quality of nearby water resources (Zaharia & Suteu, 2012). As textile production increases, effective wastewater treatment is becoming increasingly important for protecting local water bodies and meeting the discharge requirements prescribed by the HSPCB and the CPCB.Research conducted in India and other textile-producing regions has shown that properly operated ETPs can substantially reduce biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS) (Madan et al., 2024; Singh et al., 2008; Wondim et al., 2023). For example, an assessment of a polyester textile-dyeing ETP in Haridwar reported considerable reductions in colour, electrical conductivity, BOD, and COD. The study also demonstrated that conventional treatment systems may be less effective in removing certain dissolved pollutants (Madan et al., 2024).Parameters such as total dissolved solids (TDS) and electrical conductivity are particularly difficult to reduce through conventional biological treatment and sedimentation processes (Bidu et al., 2021; Rabbi et al., 2018; Wondim et al., 2023). Studies from Bangladesh and African textile-processing regions have similarly reported limited TDS removal by conventional ETPs. In some cases, TDS levels increased after treatment, possibly because of the mineralisation of organic matter and the addition of chemicals during different treatment stages (Bidu et al., 2021; Islam & Mostafa, 2020; Rabbi et al., 2018). Such findings demonstrate that ETP performance must be evaluated under site-specific operating conditions rather than assumed from the treatment design alone. The rapid growth of textile processing in Bhiwani has created a need for reliable local information on wastewater quality and treatment performance. Such information is essential for assessing regulatory compliance, determining the effectiveness of existing treatment systems, and identifying parameters or treatment stages that may require further optimization (Shah & Ruparelia, 2022).

Accordingly, the present study aimed to: (i) characterize the physicochemical properties of untreated and treated wastewater collected from a textile-processing unit in Bhiwani, Haryana; (ii) determine the removal efficiencies of the ETP for major physicochemical parameters and selected trace metals; and (iii) compare the quality of the treated effluent with the applicable CPCB discharge standards for inland surface waters.

2. MATERIAL AND METHODOLOGY

2.1 Study Area and Sample Collection

The study was conducted at a textile processing unit located in Bhiwani district, Haryana, India. Wastewater samples were collected from two locations within the effluent treatment plant (ETP) on 12 February 2026: the inlet, representing untreated wastewater entering the treatment system, and the outlet, representing the final treated effluent before discharge. Samples were collected in pre-cleaned polyethylene containers that were rinsed with the sample water before collection. The samples were transported under refrigerated conditions (approximately 4 °C) to limit microbial activity and physicochemical alteration during transit, consistent with the preservation requirements of standard wastewater protocols (Baird et al., 2017).. The samples were transported to the Department of Environmental Science, Maharshi Dayanand University, Rohtak, and analysed immediately to minimise any changes in their physicochemical characteristics. Each parameter was measured in triplicate, and the results are reported as mean ± standard deviation.

2.2 Analytical Methods

All analyses were carried out following the procedures described in the 23rd edition of APHA Standard Methods for the Examination of Water and Wastewater. (Baird et al., 2017).

The pH and temperature of the wastewater were measured in the field using a calibrated digital pH meter. Total dissolved solids (TDS) and total suspended solids (TSS) were determined using standard gravimetric methods. Total hardness was measured by EDTA titration and expressed as $CaCO_3$, while alkalinity was determined by acid titration to the phenolphthalein and mixed-indicator end points. Chloride concentration was measured by the Mohr argentometric method, sulfate by the turbidimetric method, and phosphate using the ascorbic acid colorimetric method. Colour was determined spectrophotometrically and expressed in Platinum-Cobalt (Pt-Co) units.

Biochemical oxygen demand (BOD) was determined by the standard five-day incubation method at 20°C, whereas chemical oxygen demand (COD) was measured using the closed-reflux dichromate method. Concentrations of nickel (Ni), zinc (Zn), lead (Pb), chromium (Cr), iron (Fe), manganese (Mn), cadmium (Cd), and copper (Cu) were determined by atomic absorption spectrophotometry (AAS) after acid digestion of the samples (Baird et al., 2017; Rana et al., 2017; Sarker et al., 2015).

All measurements were performed in triplicate, and the results are expressed as mean ± standard deviation (SD). Percentage removal efficiency for each parameter was calculated using influent and effluent concentrations. Since the investigation was based on paired samples collected during a single sampling event, the data were interpreted using descriptive statistics.

2.3 Data Analysis and Compliance Assessment

Treatment performance was evaluated by comparing the concentrations measured at the ETP inlet and outlet and calculating the percentage removal for each parameter using:

Removal Efficiency (%) = $[(C_i - C_o) / C_i] \times 100$

where C_i is the inlet concentration and C_o is the outlet concentration.

The quality of the treated effluent was assessed against the general discharge standards for inland surface water specified under Schedule VI of the Environment (Protection) Rules, 1986, issued by the Central Pollution Control Board (CPCB) and implemented by the Haryana State Pollution Control Board (HSPCB). For parameters without prescribed CPCB discharge limits, including chloride, sulfate, hardness, and alkalinity, the corresponding reference values from IS 2296 (Bureau of Indian Standards [BIS], 1982) were used only to provide additional context and were not considered regulatory compliance criteria

3. RESULTS

3.1 Physico-chemical characteristics of ETP inlet and outlet

Table I summarises the physicochemical characteristics of the wastewater before and after treatment, together with the applicable CPCB/HSPCB discharge standards and the removal efficiency achieved by the ETP. The untreated influent exhibited high organic loading, elevated suspended solids, alkaline pH, and measurable concentrations of dissolved salts, all of which are characteristic of textile processing wastewater (Öztürk et al., 2009; Zaharia & Suteu, 2012).. Treatment substantially improved the quality of the effluent, with all regulated parameters meeting the prescribed discharge standards.

Table I:Physico-Chemical Characteristics Of ETP Inlet And Outlet (Mean ± Sd, N = 3) With CPCB/HSPCB Standards

Parameter	Inlet (Mean ± SD)	Outlet (Mean ± SD)	CPCB/HSPCB Limit	Status	% Removal
pH	9.27 ± 0.09	7.55 ± 0.15	5.5–9.0	Complies	—
Temperature (°C)	38.3 ± 0.67	23.0 ± 0.15	≤ 5 °C above receiving water	Complies	39.8
Total Dissolved Solids, TDS (mg/L)	1283.7 ± 21.0	1041.3 ± 37.0	2100*	Complies	18.9
Total Suspended Solids, TSS (mg/L)	108.7 ± 3.1	0.97 ± 0.02	100	Complies	99.1
Total Hardness (mg/L as $CaCO_3$)	176.7 ± 1.5	130.3 ± 2.1	300**	Complies	26.2
Alkalinity, Phenolphthalein (mg/L)	38.3 ± 0.6	23.7 ± 1.5	—	—	38.3
Alkalinity, Total (mixed indicator) (mg/L)	95.7 ± 1.5	71.0 ± 1.0	200**	Complies	25.8
Chloride (mg/L)	82.0 ± 1.0	74.7 ± 1.5	600**	Complies	8.9
Sulfate (mg/L)	159.3 ± 3.1	102.3 ± 1.5	1000**	Complies	35.8
Dissolved Phosphate (mg/L)	9.23 ± 0.06	3.50 ± 0.10	5.0	Complies	62.1
Colour (Pt-Co units)	168.3 ± 3.5	41.0 ± 1.0	Qualitative***	Improved	75.6
BOD (mg/L)	268.7 ± 9.5	6.13 ± 0.15	30	Complies	97.7
COD (mg/L)	688.7 ± 9.5	33.7 ± 2.1	250	Complies	95.1
Nickel, Ni (mg/L)	0.023 ± 0.002	0.0086	3.0	Complies	62.6
Zinc, Zn (mg/L)	0.076 ± 0.002	0.031	5.0	Complies	59.2
Lead, Pb (mg/L)	0.011 ± 0.002	0.0053	0.1	Complies	51.8
Chromium, Cr (mg/L)	0.0032 ± 0.0002	0.0004	2.0 (0.1 hexavalent)	Complies	86.7
Iron, Fe (mg/L)	0.061 ± 0.002	0.0240 ± 0.0001	3.0	Complies	60.7
Manganese, Mn (mg/L)	0.049 ± 0.001	0.022	2.0	Complies	55.1
Cadmium, Cd (mg/L)	0.0019 ± 0.0001	0.0011	2.0	Complies	45.0
Copper, Cu (mg/L)	0.039 ± 0.001	0.019	3.0	Complies	51.3

** No numeric TDS limit is prescribed in CPCB Schedule VI for inland surface water; 2100 mg/L is the value commonly stipulated by SPCBs in Consent to Operate conditions for textile-sector discharge and is used here for comparison, consistent with practice in comparable regional studies.*

*** IS 2296 / irrigation-water reference values cited for context in the absence of a CPCB Schedule VI numeric limit.*

**** CPCB Schedule VI requires only that "all efforts should be made to remove colour and unpleasant odour as far as practicable" (Annexure-I, cl. 6), without a numeric limit.*

3.2 pH and Temperature

The untreated wastewater was strongly alkaline, with a mean pH of 9.27 ± 0.09. This was expected because alkaline chemicals are widely used during scouring, bleaching, and mercerizing processes (Bhatia et al., 2018; Kato & Kansha, 2024; Öztürk et al., 2009). Chemicals such as caustic soda, sodium silicate, sodium hypochlorite, and surfactants can substantially increase the pH of wastewater generated during textile pretreatment (Öztürk et al., 2009). Following treatment, the pH declined to 7.55 ± 0.15, which was within the CPCB permissible range of 5.5–9.0 for discharge into inland surface waters (Rodrigues et al., 2014). Similar changes from alkaline to near-neutral conditions have been observed in other textile ETPs (Bhatia et al., 2018). The observed decline therefore suggests that the neutralisation and subsequent treatment stages were effective in controlling the alkalinity of the wastewater.

The wastewater temperature also decreased considerably during treatment, falling from 38.3 ± 0.67 °C at the inlet to 23.0 ± 0.15 °C at the outlet. This represents a reduction of approximately 39.8%. The decrease may be attributed to the retention of wastewater in different treatment units, exposure to ambient conditions, and cooling arrangements within the ETP. Similar temperature reductions have been reported in textile treatment plants that use sequential retention tanks and cooling systems before final discharge.The outlet value indicates that the treatment process substantially reduced the thermal load of the effluent. However, formal compliance with the CPCB temperature criterion should be confirmed by comparing the outlet temperature with that of the receiving water body, because the discharge temperature should not exceed the receiving-water temperature by more than the permitted limit.

3.3 Organic Load: BOD and COD

The ETP achieved substantial removal of biodegradable and oxidisable organic matter. BOD decreased from 268.7 ± 9.5 mg/L to 6.13 ± 0.15 mg/L, corresponding to a removal efficiency of

97.7%. Similarly, COD declined from 688.7 ± 9.5 mg/L to 33.7 ± 2.1 mg/L, representing 95.1% removal. Both values were considerably lower than the CPCB discharge limits of 30 mg/L for BOD and 250 mg/L for COD (Donkadokula et al., 2020). These results demonstrate efficient removal of the organic load and indicate that the biological and oxidation stages of the ETP were operating effectively. Comparable removal efficiencies have been reported for well-managed textile treatment plants employing integrated physical, chemical, and biological treatment processes (Bidu et al., 2021; Ceretta et al., 2021; Madan et al., 2024). The biological stage—typically consisting of aerobic processes such as activated sludge or biofilm reactors—is widely recognised as the principal step responsible for organic-matter mineralisation in textile wastewater treatment (Arslan et al., 2016; Bhatia et al., 2017; Bhattacharya et al., 2022; Halepoto et al., 2022; Kumbasar & Körlü, 2016).

3.4 Suspended and Dissolved Solids

Suspended solids were removed very effectively during treatment. TSS decreased from 108.7 ± 3.1 mg/L to 0.97 ± 0.02 mg/L, corresponding to a removal efficiency of 99.1%. The treated effluent was therefore well below the CPCB discharge limit of 100 mg/L (Rana et al., 2017), indicating efficient clarification and solid–liquid separation in primary and secondary settling units (Shamsuzzaman et al., 2021; Zaharia & Suteu, 2012). In contrast, TDS showed only a modest reduction, decreasing from 1283.7 ± 21.0 mg/L to 1041.3 ± 37.0 mg/L (18.9% removal). Although the outlet concentration remained below the reference value commonly adopted for textile wastewater discharge, the limited reduction reflects the inherent difficulty of removing dissolved salts using conventional treatment processes (Bidu et al., 2021; Islam & Mostafa, 2020; Rabbi et al., 2018). Studies from Bangladesh, India, and Africa have shown that conventional textile ETPs seldom achieve TDS reductions greater than 25% (Bidu et al., 2021; Islam & Mostafa, 2020; Rabbi et al., 2018). Significant TDS reduction generally requires advanced treatment technologies such as reverse osmosis, electrodialysis, ion-exchange, or other membrane-based systems (Dow et al., 2017; Islam & Mostafa, 2020; Rizzo et al., 2019; Varma & Sharma, 2011).

3.5 Hardness, Alkalinity, Chloride, and Sulfate

Moderate reductions were observed in hardness and alkalinity following treatment. Total hardness decreased by 26.2%, while phenolphthalein and total alkalinity decreased by 38.3% and 25.8%, respectively. These changes suggest partial removal of carbonate and bicarbonate species during treatment, consistent with the partial precipitation of calcium-based hardness salts within the alkaline environment typical of textile wastewater (Babu et al., 2007; Öztürk et al., 2009; Varma & Sharma, 2011).

Chloride concentration decreased only slightly, from 82.0 mg/L to 74.7 mg/L (8.9% removal), whereas sulfate decreased from 159.3 mg/L to 102.3 mg/L, corresponding to 35.8% removal. Such behaviour is expected because dissolved ions are only minimally affected by conventional biological treatment (Dagar et al., 2022; Öktem et al., 2019). In textile effluents, chloride and sulfate arise primarily from sodium chloride used in dye fixation and sodium sulfate employed as an exhausting agent in the dyeing process, and they tend to pass through primary, secondary, and even tertiary biological stages largely unchanged (Öktem et al., 2019; Öztürk et al., 2009; Varma & Sharma, 2011).

3.6 Phosphate and Colour

Phosphate concentration decreased from 9.23 ± 0.06 mg/L in the influent to 3.50 ± 0.10 mg/L in the treated effluent, corresponding to a removal efficiency of 62.1%. When expressed as phosphate-phosphorus, the outlet concentration was below the CPCB discharge limit of 5.0 mg/L (CPCB, 1986). Phosphate in textile wastewater commonly originates from detergents, scouring chemicals, and phosphate-containing processing agents. During biological treatment, some of it is taken up by microorganisms and incorporated into the biomass, thereby lowering its concentration in the final effluent (Babu et al., 2007; Öztürk et al., 2009).

A clear improvement was also observed in effluent colour. The colour value fell from 168.3 ± 3.5 Pt–Co units before treatment to 41.0 ± 1.0 Pt–Co units after treatment, representing a reduction of 75.6%. Although the CPCB standards do not prescribe a specific numerical limit for colour, this decline shows that a substantial proportion of the dyes and other coloured compounds was removed or transformed during treatment (Bhatia et al., 2017; Collivignarelli et al., 2019; Zaharia & Suteu, 2012). Similar levels of decolourisation have been reported when coagulation, biological treatment, and adsorption are used in combination (Bhatia et al., 2017; Collivignarelli et al., 2019; Donkadokula et al., 2020; Zaharia & Suteu, 2012).

3.7 Heavy Metals

All eight trace metals were present at relatively low concentrations in the untreated wastewater, and their levels declined further after treatment. The removal efficiencies varied among the metals, ranging from 45.0% for cadmium to 86.7% for chromium. In the final effluent, the concentrations of nickel, zinc, lead, chromium, iron, manganese, cadmium, and copper were below their respective CPCB discharge limits (CPCB, 1986). Based on the measured concentrations, these metals were unlikely to present an immediate regulatory concern under the conditions examined (Halimoon & Goh, 2010; Türksoy et al., 2021).

Metals in textile wastewater may originate from metal-complex dyes, mordants, dye-fixing agents, and other processing chemicals. Within an ETP, their removal may occur through chemical precipitation, particularly under alkaline conditions, as well as through adsorption onto suspended solids and biological flocs during activated-sludge treatment (Aderonke et al., 2020; Halimoon & Goh, 2010; Kato & Kansha, 2024; Türksoy et al., 2021). Previous studies have also reported effective chromium and copper removal using additional polishing methods, including zeolite-based materials and biosorbents (Aderonke et al., 2020; Halimoon & Goh, 2010; Madan et al., 2024). Although the metal concentrations recorded in the present study were low, regular monitoring remains necessary because even small quantities can accumulate in sediments over time and may eventually affect aquatic organisms through toxicity and bioaccumulation (Türksoy et al., 2021; Wondim et al., 2023).

3.8 Statistical Analysis

Basis of analysis. The following statistical analyses use the parameter-level inlet and outlet mean values reported in Table I. Because the source table reports mean ± SD (n = 3) rather than the three individual replicate observations, the regression, correlation and PCA presented here are exploratory comparisons across water-quality parameters, not substitutes for replicate-level inferential analysis.

Table II. Exploratory Statistical Summary

Analysis	Statistic / model	Result	Interpretation
Pearson correlation	r; two-sided p	$r = 0.963$; $p < 0.001$	Very strong positive inlet-outlet association.

Spearman correlation	ρ; two-sided p	ρ = 0.884; $p < 0.001$	Strong monotonic inlet-outlet association.
Linear regression	log10 outlet vs log10 inlet	y = −0.508 + 0.946x; R^2 = 0.927	Strong descriptive cross-parameter fit.
Removal correlation	Pearson r with % removal	Inlet = −0.104; Outlet = −0.348	Removal varies substantially among constituents.
PCA	Explained variance	PC1 = 68.67%; PC2 = 31.14%; cumulative = 99.81%	PC1 reflects concentration; PC2 reflects removal efficiency.

(a) Treatment/Removal Efficiency

$$\textbf{\textit{Removal efficiency}}(\%) = \left[{(C_{in} - C_{out})}/{C_{in}}\right] \times \mathbf{100}$$

where C_{in} is the inlet concentration/value and C_{out} is the corresponding outlet concentration/value. This equation quantifies the percentage reduction across the ETP.

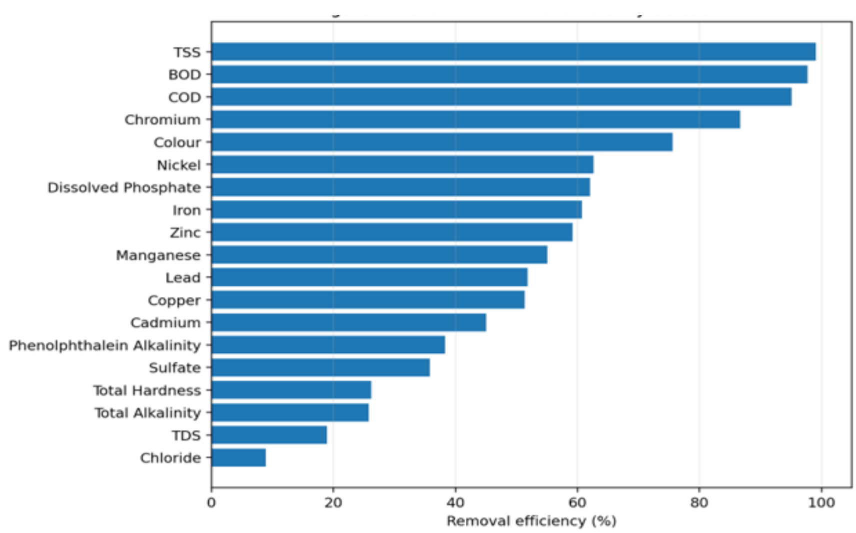

Figure 1. Pollutant removal efficiency across ETP.

(b) **Correlation Efficiency**

Pearson product-moment correlation coefficient:

$$r = \Sigma[(x_i - \bar{x})(y_i - \bar{y})] / \sqrt{\{\Sigma(x_i - \bar{x})^2 \ \Sigma(y_i - \bar{y})^2\}}$$

For log10-transformed inlet and outlet values, Pearson r = 0.963 ($p < 0.001$), indicating a very strong positive linear association. Spearman rank correlation was ρ = 0.884 ($p < 0.001$), confirming a strong monotonic association.

(c) Linear Regression

$$\hat{y} = \beta_0 + \beta_1 x + \varepsilon$$

For the present parameter-level comparison, x = log10(inlet) and y = log10(outlet). The fitted model is: log10(Outlet) = -0.508 + 0.946 × log10(Inlet), with R^2 = 0.927. Thus, approximately 92.7% of the cross-parameter variation in log-transformed outlet values is associated with the corresponding log-transformed inlet values.

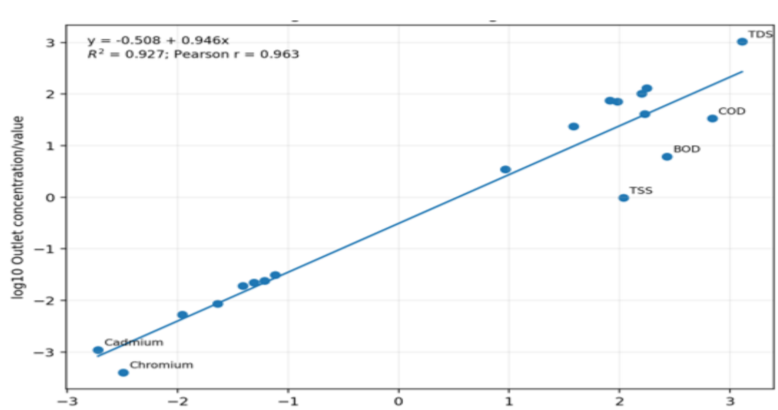

Figure 2. Inlet-outlet regression

(d) Principal Component Analysis (PCA)

$$Z_{ij} = (X_{ij} - \mu_j) / \sigma_j$$

The variables log10(inlet), log10(outlet), and removal efficiency were standardized before PCA so that variables with different numerical scales contributed comparably.

$$PC_k = a_{k1}Z_1 + a_{k2}Z_2 + \cdots + a_{kp}Z_p$$

In this exploratory parameter-level PCA, PC1 explains 68.67% and PC2 explains 31.14% of the standardized variance (cumulative = 99.81%). The score plot visualizes which measured parameters have similar or contrasting inlet-outlet-removal profiles.

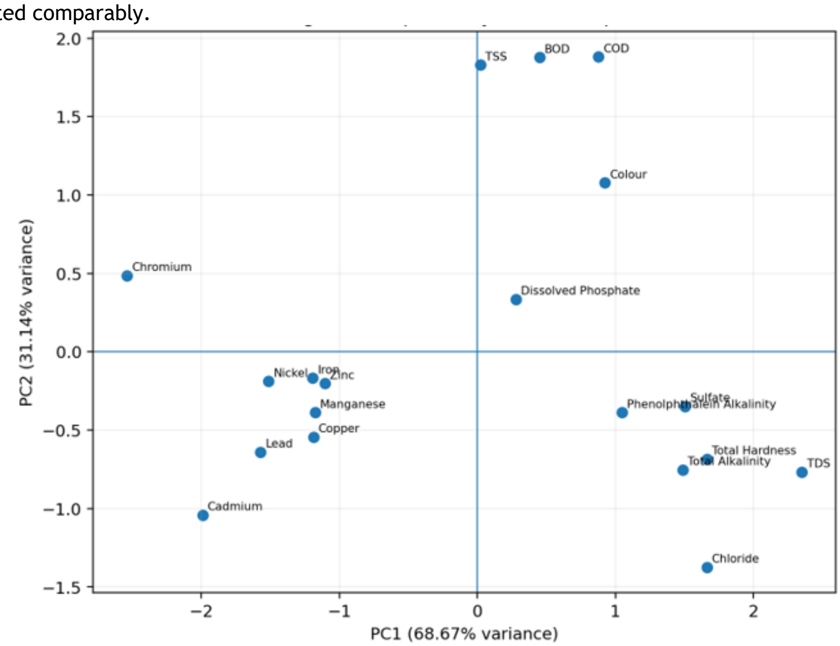

Figure 3. Exploratory PCA score plot.

“Statistical analysis of the parameter-level mean data showed a strong positive relationship between inlet and outlet water-quality values after log10 transformation (Pearson $r = 0.963$, $p < 0.001$; Spearman $\rho = 0.884$, $p < 0.001$). Linear regression yielded $R^2 = 0.927$. Exploratory PCA performed on standardized log10 inlet, log10 outlet and percentage-removal variables explained 68.67% and 31.14% of variance in PC1 and PC2, respectively. Because only summarized mean ± SD data were available, these multivariate results should be regarded as exploratory; replicate-level observations are required for confirmatory statistical inference.”

3.9 Data Comparison

Depending on the obtained data, the suggested treated effluent exhibits excellent international performance, especially for metals and TSS. Phosphorus is one significant exception. Although your stated phosphate result is 3.50 mg/L, comparability with EU/IFC total phosphorus limitations necessitates conversion and testing using the same analytical basis. EU textile BAT 2022 plus World Bank/IFC textile EHS is the most robust international comparison. The treated COD, for instance, is 33.7 mg/L, TSS is 0.97 mg/L, Ni is 0.0086 mg/L, Cr is 0.0004 mg/L, Cu is 0.019 mg/L, and Zn is 0.031 mg/L. TSS 5-30 mg/L, Cr 0.01-0.1 mg/L, Cu 0.03-0.4 mg/L, Ni 0.01-0.1 mg/L, and Zn 0.04-0.5 mg/L are among the EU 2022 textile BAT-AELs, according to the applicable requirements of the BAT decision. pH 6-9, BOD 30 mg/L, COD 160 mg/L, TSS 50 mg/L, Cd 0.02 mg/L, total Cr 0.5 mg/L, Cu/Ni 0.5 mg/L, and Zn 2 mg/L are listed in the IFC textile guideline.

Table III: Data Comparison With European And Other Standards

Parameter	Proposed outlet	India	EU BAT 2022	IFC Textile	Assessment
pH	7.55	5.5–9.0	—	6–9	Excellent
BOD (mg/L)	6.13	30	—	30	Excellent
COD (mg/L)	33.7	250	EU BAT-AEL*	160	Very good
TSS (mg/L)	0.97	100	5–30	50	Excellent
Ni (mg/L)	0.0086	3.0	0.01–0.1	0.5	Below lower EU BAT-AEL
Zn (mg/L)	0.031	5.0	0.04–0.5	2.0	Below lower EU BAT-AEL
Cr (mg/L)	0.0004	2.0†	0.01–0.1	0.5	Below lower EU BAT-AEL
Cu (mg/L)	0.019	3.0	0.03–0.4	0.5	Below lower EU BAT-AEL
Cd (mg/L)	0.0011	2.0‡	—	0.02	Below IFC guideline

"Outlet concentration as % of applicable standard," where 100% is the regulatory/guideline limit and lower values indicate a larger safety margin, is the most publication-friendly graph. Plotting BOD/COD and trace metals on the same absolute scale is avoided as a result.

Figure 4. Graphical representation of treated effluent relative to IFC guideline.

The outlet is only roughly 20.4% of the IFC BOD guideline, 21.1% of the COD guideline, and 1.9% of the TSS guideline, according to this figure 4. Additionally, the measured trace-metal concentrations only represent a tiny portion of the related IFC guideline values.

4. DISCUSSION

The current study shows that the physicochemical quality of the textile wastewater produced by the examined textile processing unit in Bhiwani, Haryana, was significantly enhanced by the effluent treatment plant. Phosphate, colour, dissolved/suspended particles, high organic load, alkaline pH, and measurable trace metal concentrations were characteristic of the untreated wastewater (Zaharia & Suteu, 2012). Most metrics showed significant decreases after treatment, and the treated effluent fulfilled the relevant discharge limitations taken into consideration in the study.

The decrease in organic pollutants was one of the most important discoveries. COD dropped from 688.7 ± 9.5 mg/L to 33.7 ± 2.1 mg/L (95.1% removal), while BOD dropped from 268.7 ± 9.5 mg/L to 6.13 ± 0.15 mg/L (97.7% removal). The CPCB limits were far below both output concentrations. The high removal efficiencies suggest that the biological and physicochemical treatment steps operated satisfactorily and that biodegradable and chemically oxidisable organic waste was effectively reduced (Donkadokula et al., 2020). Because untreated textile effluent may contain oils, sizing agents, surfactants, dyes, and other organic substances that can significantly increase oxygen demand when released into receiving waters (Babu et al., 2007; Zaharia & Suteu, 2012), the simultaneous decrease of BOD and COD is crucial.

The different behaviour of suspended and dissolved solids was an equally significant outcome. TSS dropped by 99.1%, indicating successful solid-liquid separation. TDS, on the other hand, dropped by only 18.9%. This modest clearance suggests that dissolved salts continue to be a significant treatment system constraint, with conventional textile ETPs in similar contexts achieving only limited TDS reductions (Bidu et al., 2021; Rabbi et al., 2018). Therefore, where significant TDS reduction or high-quality wastewater reuse is sought, sophisticated polishing procedures such as membrane treatment may be necessary (Dow et al., 2017).Additionally, the alkaline quality of the effluent was successfully rectified. The treated wastewater's pH dropped to 7.55 ± 0.15, and temperature dropped to 23.0 ± 0.15 °C. Because excessive pH and high temperatures can negatively affect receiving-water chemistry and aquatic life (Islam & Mostafa, 2019), these variations show that the effluent was effectively conditioned before discharge.Hardness, alkalinity, chloride, and sulphate all showed moderate to minimal decreases. The minimal reduction in TDS and the relatively low elimination of chloride (8.9%) further show that dissolved inorganic elements are generally resistant to conventional treatment methods (Bidu et al., 2021; Öktem et al., 2019; Rabbi et al., 2018). These findings imply that individual constituents react differently based on their physicochemical properties, hence ETP efficacy shouldn't be assessed solely on total pollutant removal (Wondim et al., 2023).Phosphate and colour also showed significant improvement. Dissolved phosphate dropped by 62.1%, and colour dropped by 75.6%. Because excessive nutrient release can worsen receiving water quality (Zaharia & Suteu, 2012), phosphate reduction is crucial. Significant colour removal signifies successful dye reduction through physico-chemical and biological pathways (Bhatia et al., 2017; Collivignarelli et al., 2019; Suresh, 2014).

All eight trace elements showed decreases, with metal removal occurring via precipitation, coagulation, and sludge adsorption (Donkadokula et al., 2020; Halimoon & Goh, 2010). Statistical analysis confirmed that pollutant concentrations and treatment/removal behaviour represent the primary dimensions of variation in plant performance (Wondim et al., 2023). Overall, the findings show that the examined ETP was very successful in eliminating organic pollutants and suspended particles, moderately to highly successful for colour, phosphate, and trace metals, but less successful in eliminating dissolved salts (Donkadokula et al., 2020; Rodrigues et al., 2014).

5. CONCLUSION

Effluent This study examined the textile effluent treatment plant's efficiency at the production facility in Bhiwani, Haryana.. TSS, BOD, and COD removal efficiency were quite high, while colour, phosphate, and trace metals were also significantly decreased. The study's applicable discharge criteria were satisfied by the treated effluent. Conversely, somewhat less removal of hardness, TDS, chloride, and other dissolved ionic compounds suggests that conventional treatment is less successful for dissolved salts. The treatment trend was further validated by the statistical analysis. Inlet and outflow values had strong Pearson and Spearman correlations, and the regression model had a high coefficient of determination. Additionally, exploratory PCA revealed that the main dimensions of variance in the dataset were pollutant concentration and removal behaviour. However, these statistical results should be viewed as exploratory since the analysis was primarily based on parameter-level mean values from a single sampling event. Overall, the results show that the ETP works very well for organic and suspended pollution, although dissolved solids continue to be the primary area in need of improvement.

Future studies should therefore focus on long-term monitoring across different seasons, production cyclesTherefore, in order to assess the consistency of ETP performance, future research should concentrate on long-term monitoring across various seasons, production cycles, and operational situations. Additionally, more reliable correlation, regression, and PCA analysis would be possible with several independent sample events. In order to reduce TDS, chloride, residual colour, and other persistent dissolved impurities, further research may assess advanced treatment alternatives such reverse osmosis, nanofiltration, adsorption, advanced oxidation, or other polishing procedures. These advancements could lessen reliance on freshwater resources and increase the possibility of treated water reuse in textile operations.

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