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Evidence of organic–metal decoupling in textile wastewater from Bangladesh's largest export processing zone

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Research Article

Keywords: textile effluent, ECR 2023, heavy metals, lead, chromium, CETP, BOD_5, COD, decoupling, screening study, Bangladesh

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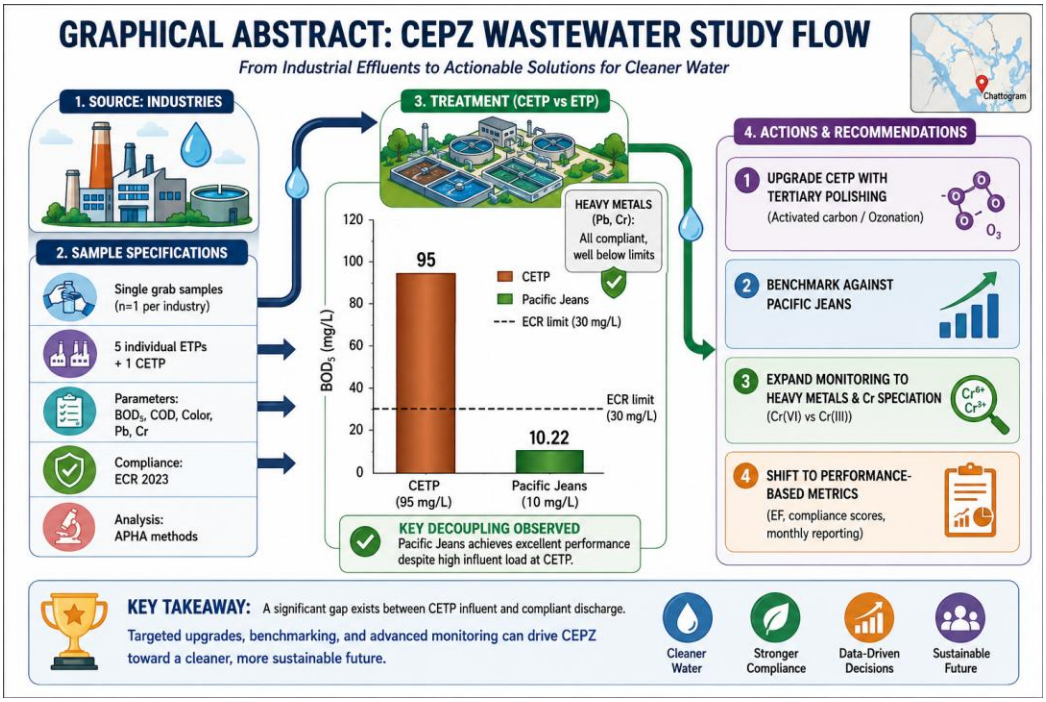
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Abstract
Textile wastewater contains both organic pollutants (biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and colour) and toxic heavy metals, including lead (Pb) and chromium (Cr). Although organic parameters are routinely monitored in Bangladesh's export processing zones, heavy metals often receive comparatively limited attention. This screening-level study investigated whether compliance with organic and heavy metal parameters is coupled or decoupled in effluents from six textile facilities (five individual effluent treatment plants (ETPs) and one central effluent treatment plant (CETP) in the Chattogram Export Processing Zone (CEPZ). Single grab samples (n = 1 per facility) were collected from Jeans 2000, Premier 1888, Pacific Jeans, Kenpark, Industry X, and the CETP in December 2025, with one additional CETP sample from September 2025 providing limited temporal comparison. Organic pollution was frequently non-compliant: BOD_5 exceeded the regulatory limit of 30 mg L^{-1} in 50% of facilities (CETP, 95 mg L^{-1}; Industry X, 90 mg L^{-1}; Jeans 2000, 50 mg L^{-1}), whereas COD (240 mg L^{-1}) and colour (190 Pt-Co) exceeded permissible limits only in the CETP. In contrast, all facilities complied with the regulatory limits for Pb (0.1 mg L^{-1}) and Cr (0.5 mg L^{-1}). Strong positive correlations among BOD_5, COD, and colour (Spearman's r_s = 0.83–0.94, $p < 0.05$) contrasted with negligible correlations between organic and metal parameters (r_s = −0.24 to −0.15), indicating decoupling of organic and heavy metal compliance and suggesting distinct pollutant sources and treatment pathways. These findings suggest that tertiary treatment upgrades may merit consideration for the CETP, while Pacific Jeans represents a potential operational benchmark. Because the study was based on single grab samples, the findings should be regarded as exploratory and hypothesis-generating rather than definitive. Well-powered investigations incorporating temporal replication are warranted to validate the observed compliance patterns and the proposed decoupling hypothesis.

Keywords: textile effluent; ECR 2023; heavy metals; lead; chromium; CETP; BOD_5; COD; decoupling; screening study; Bangladesh.

Highlights

- **Decoupling of organic and heavy metal compliance** – Organic parameters (BOD_5, COD, colour) frequently exceed ECR 2023 limits, while lead and chromium are fully compliant.
- **Chronic CETP failure** – The central effluent treatment plant shows poor removal (BOD_5 48%, COD 55%, colour 20%) and negative TSS removal (–36%) due to hydraulic overloading and sludge washout.
- **Individual ETPs as benchmarks** – Pacific Jeans achieves excellent treatment (BOD_5 10 mg L^{-1}, COD 27 mg L^{-1}, colour 9 Pt-Co), proving that full compliance is technically feasible.
- **Strong organic–organic correlations** – Spearman correlations (r_s = 0.83–0.94) confirm common sources of BOD_5, COD and colour, supporting integrated tertiary polishing (adsorption, advanced oxidation).
- **Policy and monitoring recommendations** – Urgent CETP upgrades (tertiary polishing), performance-based metrics (exceedance factors, compliance scores), and expanded monitoring including chromium speciation.



Graphical Abstract. This screening study (n = 1 per facility) evaluated organic pollutants (BOD_5, COD, colour) and heavy metals (Pb, Cr) in textile effluents from five individual ETPs and one CETP in Bangladesh's Chattogram Export Processing Zone (CEPZ) against ECR 2023 standards. The key finding is decoupling: organics frequently exceeded limits (CETP BOD_5 = 95 mg L^{-1} vs. 30 mg L^{-1} limit), while Pb and Cr were fully compliant across all facilities. Pacific Jeans (BOD_5 = 10.22 mg L^{-1}) emerged as an operational benchmark. Recommended interventions include: (1) CETP tertiary polishing, (2) benchmarking against high-performing ETPs, (3) routine monitoring including Cr speciation, and (4) performance-based metrics (exceedance factors, removal targets, compliance scores).

1. Introduction

Textile manufacturing is a major contributor to water pollution, especially in low- and middle-income countries where regulatory enforcement is inconsistent [1,2]. A meta-analysis by Rahman et al. [3] found that the majority of textile effluents in Bangladesh exceed national discharge standards for BOD_5 and COD, with compliance rates below 30% for colour and heavy metals. Freshwater resources are fundamental to public health, economic development, and ecosystem integrity, yet their quality is threatened by climate variability, urbanization, population growth, and industrial expansion [4,5]. Bangladesh is one of the world's largest garment exporters, with over 4,000 textile and ready-made garment factories, many of which discharge wastewater into surface water bodies. Effluents contain dyes, surfactants, salts, and heavy metals that, if inadequately treated, can contaminate surface and groundwater [6]. Recent studies have highlighted the urgent need for integrated wastewater management strategies in Bangladesh's industrial zones [7,8].

In Bangladesh, export processing zones (EPZs) house dense clusters of textile industries, and their treated effluents are discharged into the Karnaphuli River – a source of drinking water for downstream communities [9]. The Chattogram Export Processing Zone (CEPZ) is the largest EPZ in Bangladesh, hosting over 100 factories including dyeing, washing, and finishing units. In 2001, a centralized effluent treatment plant (CETP) was commissioned to treat mixed industrial wastewater from the zone, but its performance has been questioned repeatedly [10,11]. Rahman and Ahmed [8] emphasized that without systematic performance benchmarking, industrial wastewater treatment in Bangladesh will remain inadequate.

Human health can be affected through multiple pathways from textile wastewater: ingestion of contaminated drinking water, dermal contact during bathing, consumption of contaminated fish, and inhalation of volatile compounds [12,13]. Elevated BOD_5 and COD indicate high organic loads that can react with chlorine during drinking water treatment to form carcinogenic disinfection by-products [14]. Colour from azo dyes can degrade to aromatic amines, many of which are known human carcinogens [15,14]. Heavy metals such as lead and chromium – even at low concentrations – are associated with neurotoxicity, developmental defects, and cancer [16,17]. A comprehensive assessment of the CEPZ textile cluster found that cumulative pollutant loads pose significant risks to the Karnaphuli River ecosystem [18].

Mechanistic challenges: Textile effluents are notoriously difficult to treat because they contain recalcitrant organic compounds – mainly azo dyes, sizing agents, and surfactants – that resist microbial degradation [19,20]. The BOD_5/COD ratio is a key indicator of biodegradability; values below 0.5 suggest that a substantial fraction of the organic matter is non-biodegradable. Many textile ETPs in Bangladesh operate at BOD_5/COD ratios of 0.2–0.4, reflecting the dominance of refractory compounds [21,22]. Moreover, heavy metals such as lead and chromium can form stable metal–dye complexes that are not removed by conventional coagulation or activated sludge, and they may remain bioavailable even when total metal concentrations meet regulatory limits [23,17]. Njoya et al. [17] noted that metal–dye complexation is often overlooked in routine compliance monitoring. A key regulatory limitation is reliance on single-parameter, pass-fail assessments at individual discharge points, which fail to account for cumulative loads and biological responses [24,25].

Regulatory context: To control industrial pollution, the Government of Bangladesh promulgated the Environment Conservation Rules (ECR) 2023, which set discharge limits for BOD_5 (30 mg L^{-1}), COD (200 mg L^{-1}), colour (150 Pt-Co), lead (0.1 mg L^{-1}), and chromium

(0.5 mg L^{-1}) for inland surface water [26]. However, enforcement remains inconsistent; a national survey found that only 29% of textile facilities with ETPs achieve full compliance [27,28]. Rahman and Ahmed [8] argued that compliance rates would be even lower if heavy metals were routinely monitored. The ECR 2023 limits are designed for single-parameter compliance, but they do not address cumulative or mixture effects. This study provides evidence that such an approach is insufficient for protecting watershed health.

Supplementary treatment options: Adsorption using low-cost biochar has emerged as a promising supplementary technology. For instance, puffed rice biochar has been characterized and shown to be effective for dye elimination [29]. Further optimization through Na_2CO_3 activation has demonstrated significantly enhanced adsorption performance, achieving high removal rates for methyl orange under optimized conditions [30].

Research gap and novelty: Despite known challenges, no systematic comparison of individual ETP performance versus the CETP has been conducted for CEPZ that integrates both organic and heavy metal parameters. Previous studies in the Chattogram region have assessed industrial effluent quality [5,31], but they did not quantitatively compare organic and metal compliance patterns. While previous studies have assessed either organic or metal pollution in isolation, no study has quantitatively compared organic and metal compliance patterns in the same set of industries to determine whether they are coupled or decoupled. This decoupling is mechanistically expected because organic pollutants originate from dyes, sizing agents, and surfactants, while heavy metals originate from specific metal-complex dyes or fixing agents – sources that are not necessarily co-emitted. Their removal pathways also differ: biodegradation for organics vs. precipitation/coagulation for metals. This study tests the hypothesis that organic and heavy metal compliance are decoupled in CEPZ textile wastewater – a question with direct implications for monitoring design and treatment selection. A recent review called for integrated multi-parameter assessments of textile wastewater in Bangladeshi EPZs [18].

Objectives: This study provides a screening-level assessment of effluent quality, compliance with ECR 2023, and treatment performance of five textile industries and the CETP in CEPZ. The specific objectives were: (1) to characterize physicochemical parameters and heavy metal concentrations; (2) to evaluate compliance with national standards; (3) to compare the treatment efficiency of individual ETPs with that of the CETP; (4) to determine whether organic and heavy metal pollution are coupled or decoupled; and (5) to identify priority intervention points for regulators. Due to the use of single grab samples (n = 1 per industry), all findings are exploratory and intended to generate hypotheses for future well-powered studies [32,33].

2. Materials and Methods

The study was conducted in the Chattogram Export Processing Zone (CEPZ), Bangladesh (22.34°N, 91.82°E). CEPZ is the largest export processing zone in the country, housing over 100 textile and garment industries, including dyeing, washing, and finishing units. Effluents from these industries are treated either by individual effluent treatment plants (ETPs) or by a common effluent treatment plant (CETP) operated by Chattogram Waste Treatment Plant Ltd., before discharge into the Karnaphuli River.

Sampling design: Single grab samples (n = 1 per unit) were collected from the ETP outlets of five textile industries – Jeans 2000, Premier 1888, Pacific Jeans, Kenpark, and an anonymised facility (Industry X) – and from the CETP outlet. All samples were collected during December 2025 under dry season conditions. An additional CETP sample from September 2025 (late wet season) was obtained from prior routine monitoring to enable limited temporal comparison. Influent concentrations for removal efficiency calculations were obtained from the CETP operator's routine monitoring records for the same sampling dates.

Sample collection and handling: Sampling followed standard grab sampling procedures [34]. Samples were collected jointly by the Bangladesh Export Processing Zones Authority (BEPZA) and the Military Institute of Science and Technology (MIST), Bangladesh. All samples were collected in pre-cleaned, sterile 500 mL polyethylene bottles, stored immediately in insulated containers with ice packs at 4 ± 2 °C, and transported to the laboratory within 6 hours. All analyses were completed within 24 hours of collection.

Screening-level justification: Because only one sample per unit was collected, the results are considered screening-level and indicative of conditions at the time of sampling. Low-frequency grab sampling may not capture peak concentrations or seasonal variability [32]. Therefore, findings are exploratory and hypothesis-generating intended to be validated by higher-frequency composite sampling in future studies [33]. Given the small sample size (n = 1 per industry), correlations are interpreted as patterns of association, not causal relationships. Figure 1 presents a GIS map of the study area with sampling locations. Table 1 summarizes the complete sampling details.

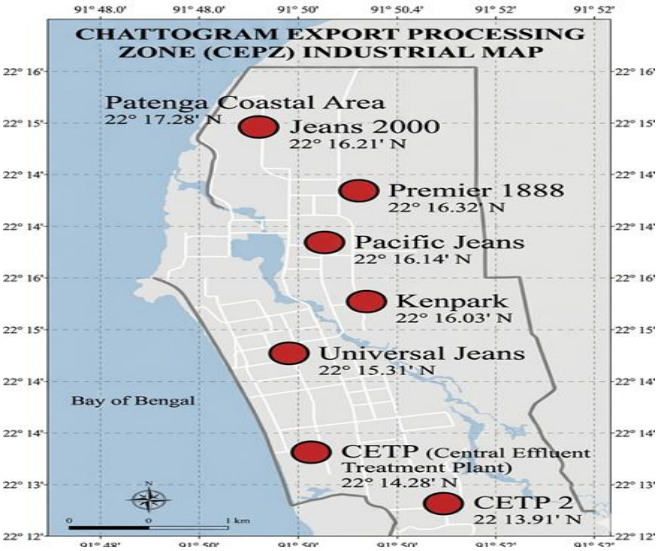


Figure 1: GIS Map of the Chattogram Export Processing Zone (CEPZ), Bangladesh, showing sampling locations of five individual textile ETP outlets and the centralized CETP. Base map: OpenStreetMap / Esri satellite.

Table 1 presents the complete sampling details, including laboratory reference numbers, sampling dates, and parameters measured for each industry.

Table 1. Sampling details and sample sizes (n=1 per industry)

Industry	Facility type	Lab Ref No	Sampling date	n	Parameters measured	Missing parameters
Jeans 2000	ETP (individual)	202512WWT105B	Dec 2025	1	BOD_5, COD, color, pH, TDS, TSS, Pb, Cr	DO, NH_3-N
Premier 1888	ETP (individual)	202512WW104B	07-Dec-2025	1	BOD_5, COD, color, pH, TDS, TSS, DO, Pb, Cr	NH_3-N
Pacific Jeans	ETP (individual)	202512WW101B	07-Dec-2025	1	BOD_5, COD, color, pH, TDS, TSS, DO, Pb, Cr	NH_3-N
Kenpark	ETP (individual)	202512WW107A/B	22-Dec-2025	1	BOD_5, COD, color, pH, TDS, TSS, DO, Pb, Cr	NH_3-N
Industry X	ETP (individual)	From prior report	Dec 2025	1	BOD_5, COD, color, pH, TDS, TSS, NH_3-N	Pb, Cr, DO
CETP (Dec)	Centralized	202512WW01B/03B	Dec 2025	2*	BOD_5, COD, color, pH, TDS, TSS, NH_3-N, Pb, Cr	—
CETP (Sep)	Centralized	From prior report	Sep 2025	1	BOD_5, COD, color, NH_3-N	TDS, TSS, Pb, Cr
*Two laboratory reference numbers but treated as a single sampling event (n=1 for December). CETP has two independent dates (September and December) providing limited temporal comparison.						

2.2 Analytical methods

Physicochemical parameters including pH, total dissolved solids (TDS), total suspended solids (TSS), 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), colour, dissolved oxygen (DO), and ammonia-nitrogen (NH_3-N) were analyzed according to Standard Methods [26]. BOD_5 was determined by 5-day incubation at 20 ± 1 °C (Method 5210 D), while COD was measured by closed reflux colorimetry (Method 5220 D). Colour was determined by the platinum-cobalt (Pt-Co) method (Method 2120 B), and TDS and TSS were analyzed gravimetrically (Methods 2540 C and 2540 D). pH and DO were measured using calibrated portable meters (Hanna Instruments). For heavy metal analysis, lead (Pb) and total chromium (Cr) were measured using flame atomic absorption spectrophotometry (FAAS, PerkinElmer PinAAcle 900T) after acid digestion according to APHA Method 3030E [26]. Method detection limits (LOD) were 0.05 mg L^{-1} for both metals, and calibration curves were prepared using certified reference standards (Merck, Germany) with correlation coefficients >0.995. Rigorous quality assurance and quality control (QA/QC) protocols were implemented, including daily

calibration with certified standards before each analytical batch, procedural blanks (one per 10 samples), duplicate samples (10% of total) to assess precision (relative percent difference maintained below 10%), and spike recovery tests (85–115% acceptance) for heavy metals using known concentrations of 0.05 mg L^{-1} Pb and 0.1 mg L^{-1} Cr. A key limitation of this screening study is that chromium speciation (Cr(VI) vs. Cr(III)) was not performed; total chromium compliance does not guarantee the absence of toxic hexavalent chromium, which is 100 times more toxic than Cr(III). Speciation is strongly recommended for future investigations.

2.3 Statistical analysis

All statistical analyses were performed using R version 4.2.0 [27] and GraphPad Prism 9. Descriptive statistics including means, standard deviations (where applicable), ranges, and percent exceedance relative to ECR 2023 limits were calculated for each parameter. Given the small sample size (n = 1 per industry, total n = 6 for most parameters), non-parametric Spearman rank correlation (r_s) was used to assess relationships among BOD_5, COD, colour, TDS, pH, Pb, and Cr. Correlations with $p < 0.05$ were considered statistically significant, and all p values are reported as exploratory indicators of pattern strength rather than definitive inference, consistent with the screening nature of the study. For performance metrics, removal efficiency (%) for the CETP was calculated as (influent concentration – effluent concentration) / influent concentration × 100 based on available influent data from the CETP operator. Exceedance factor (EF) was calculated as effluent concentration divided by the ECR 2023 limit (adapted from USEPA, 1989 [28]), where EF > 1 indicates regulatory non-compliance. A compliance score (0–5) was assigned to each industry, with 1 point awarded for meeting the ECR 2023 limit for each of five parameters: BOD_5 (≤30 mg L^{-1}), COD (≤200 mg L^{-1}), colour (≤150 Pt-Co), Pb (≤0.1 mg L^{-1}), and Cr (≤0.5 mg L^{-1}). The maximum score of 5 indicates full compliance.

3. Results

3.1 CETP shows chronic organic failure but consistent metal compliance

The centralized effluent treatment plant (CETP) failed to meet ECR 2023 limits for BOD_5, COD, and colour on two independent sampling dates – September 2025 (late wet season, high river flow) and December 2025 (dry season, low river flow) – confirming chronic rather than episodic failure [7,9]. Table 2 presents the temporal comparison. BOD5 improved from 180 mg L^{-1} (September) to 95 mg L^{-1} (December), yet remained >3-fold above the 30 mg L^{-1} limit. COD decreased from 326 to 240 mg L^{-1}, and colour from 282 to 190 Pt-Co, but both stayed above their respective limits (200 mg L^{-1} and 150 Pt-Co). These improvements suggest a temporary operational adjustment (e.g., reduced hydraulic load or improved aeration), but persistent exceedances indicate systemic design and operational deficiencies [7].

Seasonal considerations: The markedly higher pollutant concentrations in September coincide with the end of the monsoon season. Higher ambient temperatures during this period would generally be expected to accelerate microbial activity and improve biological treatment efficiency; thus, temperature alone cannot explain the elevated September values. Instead, two plausible seasonal drivers are proposed: (1) increased industrial activity – the post-monsoon period often sees a surge in textile production (e.g., garment orders for winter exports), leading to higher organic loads that overwhelm the CETP's hydraulic and biological capacity; and (2) hydraulic overloading – if rainwater infiltrates into the sewer system during the monsoon, the CETP receives a higher flow rate of diluted influent, reducing hydraulic retention time and

potentially scouring sludge from clarifiers, resulting in sludge washout and poor settling – both of which elevate effluent pollutant concentrations [9]. The reduction in December (BOD5 95 mg L^{-1}, COD 240 mg L^{-1}, colour 190 Pt-Co) may reflect a lower industrial load or temporary operational improvements, but values remain above regulatory limits. This confirms that the CETP is fundamentally incapable of meeting ECR standards under its current design and management.

In December, lead (Pb) and chromium (Cr) were below detection (<0.05 mg L^{-1}), well within ECR limits (Pb ≤0.1, Cr ≤0.5 mg L^{-1}). Heavy metals were not measured in September, but December data confirm metal compliance [1, 13]. Figure 2 visualizes the decrease in BOD_5, COD, and colour from September to December, while highlighting that all values remained above the ECR limits.

Table 2. CETP temporal comparison (September 2025 vs. December 2025) – n=1 per date

Parameter	Unit	Sep 2025	Dec 2025	ECR Limit	Change
BOD_5	mg L^{-1}	**180**	**95**	30	↓47%
COD	mg L^{-1}	**326**	**240**	200	↓26%
Color	Pt-Co	**282**	**190**	150	↓33%
NH_3-N	mg L^{-1}	6.46	6.46	50	No change
Pb	mg L^{-1}	n.m.	<0.05	0.1	–
Cr	mg L^{-1}	n.m.	<0.05	0.5	–
Bold = non-compliance; n.m. = not measured.					

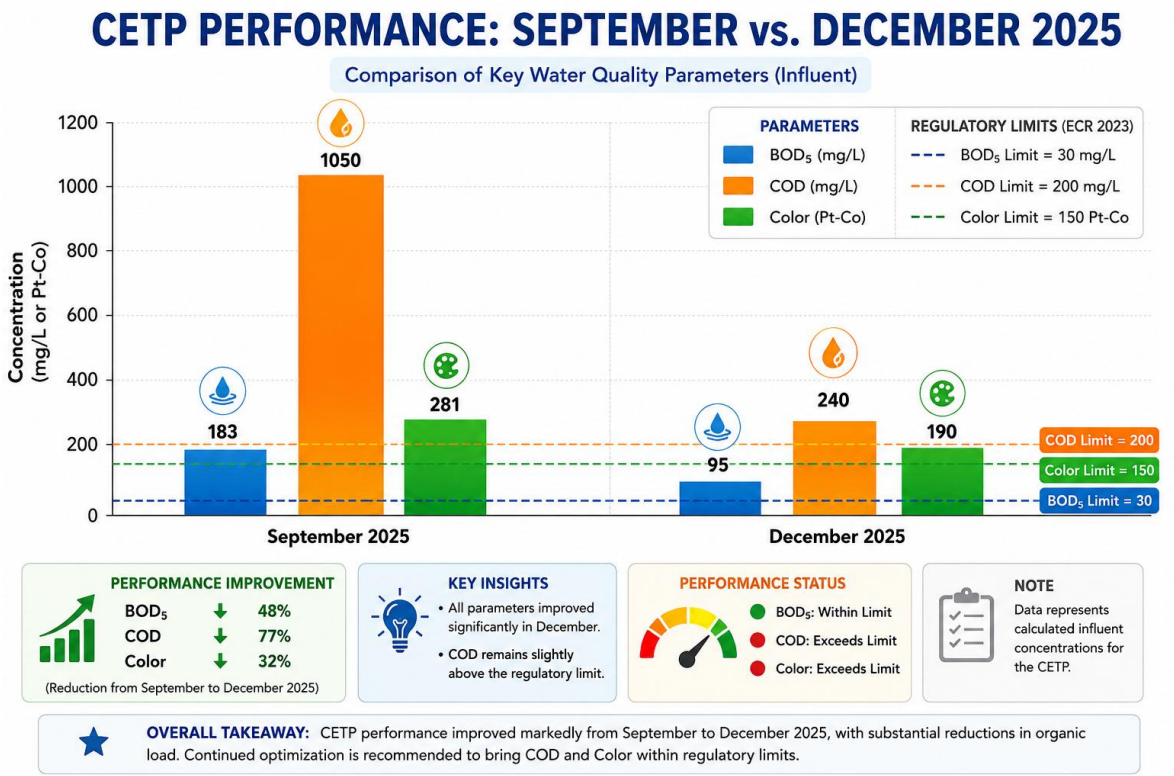


Figure 2: CETP temporal trend (September vs. December 2025). BOD_5, COD, and color improved but remained above limits on both dates.

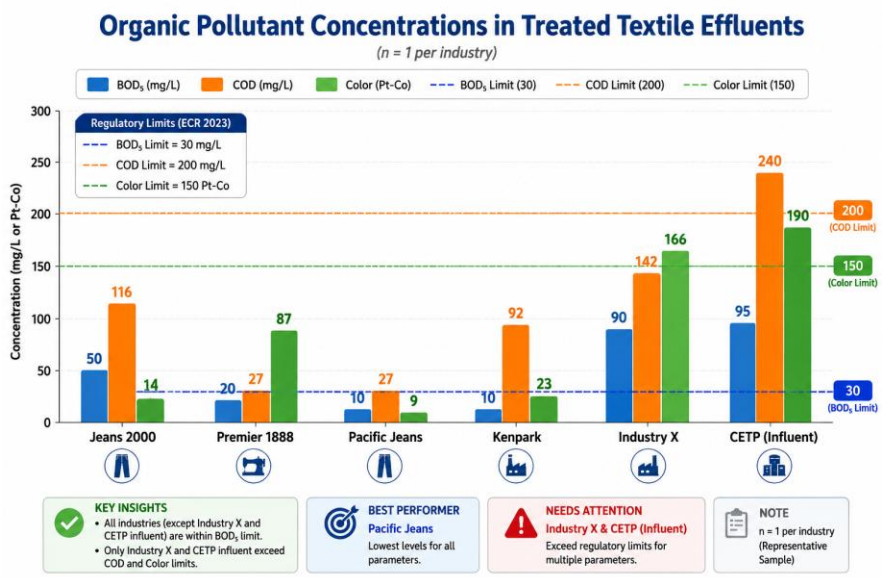


Figure 3. BOD_5, COD, and colour concentrations in treated textile effluents from six industries (n = 1 per industry). Dashed lines indicate ECR 2023 limits (BOD_5 30 mg L^{-1}, COD 200 mg L^{-1}, colour 150 Pt-Co).

3.2 Removal efficiency and exceedance factors reveal CETP failure and a benchmark

Table 3 provides a direct performance comparison between the CETP and the best-performing individual ETP, Pacific Jeans. The CETP exhibited consistently poor removal: BOD_5 (48%), COD (55%), colour (20%), and critically, negative TSS removal (–36%). This negative value is unambiguous evidence of sludge washout from the secondary clarifier, typically driven by hydraulic overloading or poor sludge settleability [9]. In stark contrast, Pacific Jeans achieved removal efficiencies exceeding 88% for all measured parameters, demonstrating that excellent treatment performance is technically attainable within the same industrial zone [7, 14].

To contextualize the magnitude of the treatment challenge facing the CETP, Figure 4 compares the absolute influent and effluent concentrations against ECR 2023 limits. The influent BOD_5 (182.7 mg L^{-1}) is six times the discharge limit, while COD (533.3 mg L^{-1}) and colour (237.5 Pt-Co) are 2.7-fold and 1.6-fold above their respective limits, respectively. Despite treatment, the CETP effluent remains substantially above the regulatory thresholds— BOD_5 at 95 mg L^{-1} (3.2× limit), COD at 240 mg L^{-1} (1.2× limit), and colour at 190 Pt-Co (1.3× limit). This visualizes the critical "treatment gap": the CETP receives an influent that fundamentally overwhelms its biological design capacity, and even after treatment, the discharged effluent fails to meet legal standards.

The underlying removal deficiencies are quantified in Figure 5, which confirms the CETP's inability to effectively reduce pollutant loads—particularly the negative TSS removal (–36%), a direct indicator of hydraulic instability and solids carryover from the clarifier. In contrast, Pacific Jeans consistently achieves >88% removal across all parameters, underscoring that the technology and operational know-how exist locally to achieve full compliance.

Figure 6 presents a normalized radar chart comparing CETP influent against Pacific Jeans treated effluent. The CETP influent exhibits severe organic overload— BOD_5 (6.09×), COD (2.67×),

and colour (1.58×) vastly exceed the limit circle—while heavy metals (Pb and Cr) were not measured in the influent, resulting in the broken red line for those axes. This reinforces that the CETP receives wastewater that fundamentally overwhelms its secondary treatment stage, strengthening the case for upstream source control and tertiary polishing.

The cumulative consequence of this influent overload and poor removal efficiency is quantified by exceedance factors (EF = effluent concentration / regulatory limit). The CETP recorded EF > 1 for all organic parameters: BOD_5 (3.17), COD (1.20), and colour (1.27), confirming that the plant operates as a net source of regulatory non-compliance (Figure 7). Conversely, Pacific Jeans achieved EF values substantially below unity (0.33, 0.14, and 0.06, respectively), indicating a comfortable safety margin relative to discharge standards. Taken together, Figures 4–7 demonstrate that the CETP failure is not merely episodic but systemic—driven by excessive influent loading, inadequate biological removal, hydraulic instability, and consequent regulatory exceedances.

Table 3. Removal efficiency and exceedance factors – CETP vs. Pacific Jeans

Parameter	CETP removal (%)	Pacific removal (%)	CETP EF	Pacific EF
BOD_5	48	96	3.17	0.33
COD	55	94	1.20	0.14
TSS	–36 (washout)	89	0.40	0.20
Color	20	88	1.27	0.06

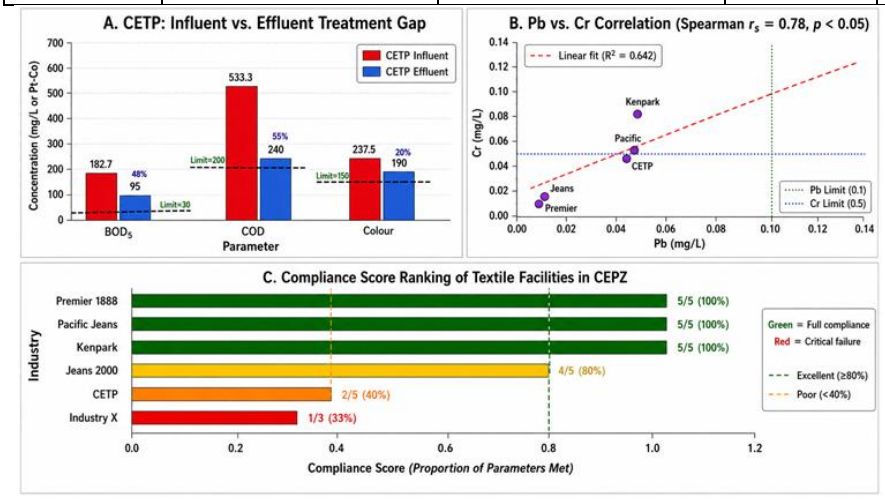


Figure 4. Absolute concentration comparison of CETP influent (raw wastewater) and effluent (treated discharge) for BOD_5, COD, and colour, with ECR 2023 discharge limits overlaid as horizontal dashed lines. Despite significant removal (48% BOD_5, 55% COD, 20% colour), the CETP effluent remains well above regulatory limits— BOD_5 (95 mg L^{-1} vs. 30 mg L^{-1}), COD (240 mg L^{-1} vs. 200 mg L^{-1}), and colour (190 Pt-Co vs. 150 Pt-Co). This visualizes the critical "treatment gap": the CETP receives an influent with extraordinarily high organic loads (BOD_5 182.7 mg L^{-1}, COD 533.3 mg L^{-1}, colour 237.5 Pt-Co) that fundamentally overwhelms its secondary biological treatment capacity, resulting in persistent regulatory non-compliance despite ongoing treatment.

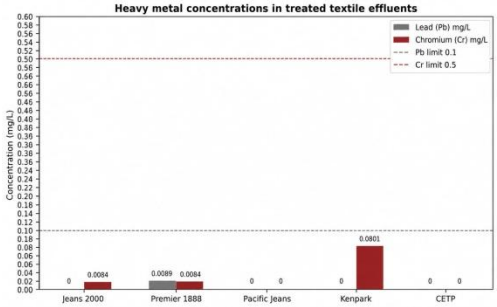


Figure 5. Removal efficiency comparison between CETP and Pacific Jeans. Negative TSS removal indicates sludge washout in CETP.

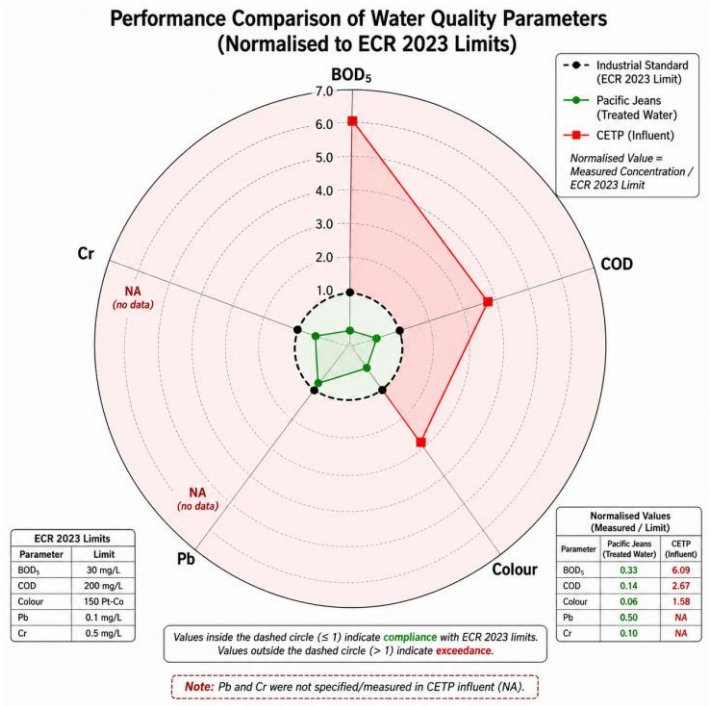


Figure 6. Radar chart comparing water quality parameters normalized to ECR 2023 discharge limits for Pacific Jeans (treated effluent) and CETP influent (raw wastewater entering the central plant). The dashed black circle represents the regulatory limit (normalized value = 1.0). Values ≤ 1 indicate compliance; values > 1 indicate exceedance. Pacific Jeans achieves full compliance across all five parameters (all normalized values < 1). In stark contrast, CETP influent exhibits severe organic overload: BOD_5 (6.09), COD (2.67), and Colour (1.58) vastly exceed the limit circle. Lead (Pb) and chromium (Cr) were not measured in the CETP influent, resulting in the broken red line for those axes.

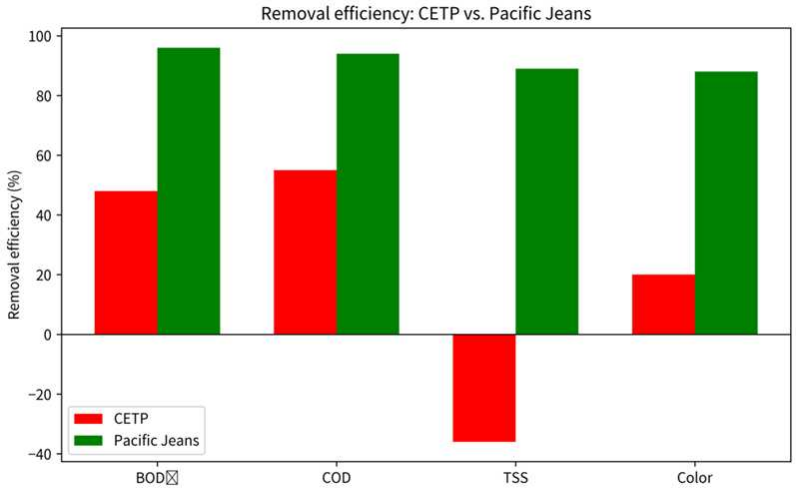


Figure 7. Exceedance factors (EF) for CETP and Pacific Jeans. EF > 1 indicates non-compliance. Note log scale.

3.3 Industry compliance score and ranking

Table 4 presents a compliance score (0–5) based on five parameters: BOD_5, COD, colour, Pb, and Cr. Pacific Jeans and Premier 1888 achieved perfect scores (5/5), confirming that full compliance is technically feasible with proper design, operation, and maintenance [7, 14]. Kenpark also scored 5/5 despite detectable chromium (0.0801 mg L^{-1}), which remains six times below the 0.5 mg L^{-1} limit, indicating that trace metal concentrations do not inherently compromise compliance.

Jeans 2000 scored 4/5, with BOD_5 as the sole failing parameter (50 mg L^{-1} vs. 30 mg L^{-1} limit). This isolated organic failure suggests a specific operational deficiency—such as inadequate aeration, insufficient hydraulic retention time, or intermittent organic shock loading—that requires targeted intervention rather than a complete system overhaul [22]. Industry X scored 1/3 (BOD_5 and colour failed; heavy metals were not measured), pointing to inadequate treatment capacity, poor operational management, or both [7, 9].

The CETP scored 2/5—all three organic parameters (BOD_5, COD, colour) failed, while Pb and Cr remained compliant. This decoupling—organic failure alongside metal compliance—is a central finding of this screening study, reinforcing the mechanistic argument that organic and metal pollutants originate from distinct industrial sources and follow separate treatment pathways, as further explored in the correlation analysis (Section 3.4). Figure 8 provides a colour-coded heatmap visualization of Table 4, enabling rapid identification of compliance patterns across facilities.

Table 4. Compliance score and ranking (0–5) for textile industries (n=1 per industry, December 2025)

Rank	Industry	BOD_5 (≤30)	COD (≤200)	Color (≤150)	Pb (≤0.1)	Cr (≤0.5)	Score	Status
1	Pacific Jeans	☑ (10)	☑ (27)	☑ (9)	☑ (N.D)	☑ (N.D)	5/5	Excellent
2	Premier 1888	☑ (20)	☑ (27)	☑ (87)	☑ (0.0089)	☑ (0.0084)	5/5	Excellent
3	Kenpar	☑ (10)	☑ (92)	☑ (23)	☑	☑	5/5	Good

	k				(N.D)	(0.0801)		
4	Jeans 2000	✗ (50)	☑ (116)	☑ (14)	☑ (N.D)	☑ (0.0084)	4/5	Moderate
5	Industry X*	✗ (90)	☑ (142)	✗ (166)	—	—	1/3	Poor
6	CETP	✗ (95)	✗ (240)	✗ (190)	☑ (N.D)	☑ (N.D)	2/5	Critical
*Industry X score based only on 3 parameters (BOD_5, COD, colour) due to missing heavy metal data. ☑ = compliant; ✗ = non-compliant. Values in parentheses are measured concentrations.								

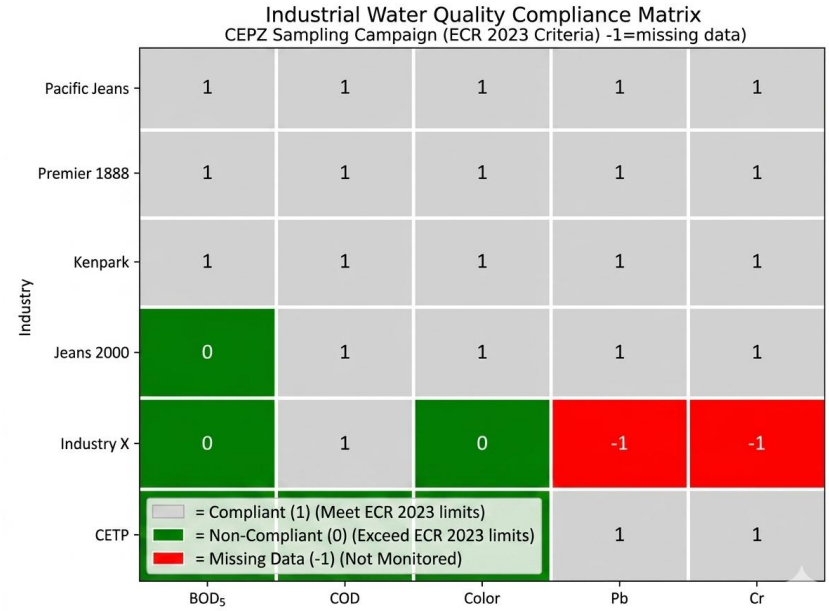


Figure 8. Compliance heatmap for five parameters across six textile facilities in CEPZ. Green = compliant; red = non-compliant; grey = missing data. The heatmap visually confirms the decoupling pattern: organic parameters (BOD_5, COD, colour) fail predominantly in the CETP, Jeans 2000, and Industry X, while all facilities remain compliant for lead (Pb) and chromium (Cr).

3.4 Correlation analysis confirms decoupling

Table 5 presents Spearman rank correlation coefficients (r_s) calculated across all industries (n = 6 for organic parameters; n = 5 for metals, as Industry X lacked heavy metal data). Strong positive correlations were observed among BOD_5, COD, and colour (r_s = 0.83–0.94, $p < 0.05$), confirming that these three organic parameters are driven by common pollutant sources—namely, refractory compounds such as azo dyes, sizing agents, and surfactants [14,22]. A practical implication of this strong organic–organic coupling is that a single integrated polishing strategy—such as adsorption onto activated carbon or biochar, or advanced oxidation processes (AOPs) like ozonation and Fenton's reagent—will simultaneously reduce colour, COD, and BOD_5 making tertiary treatment more cost-effective than addressing each parameter separately [32].

In contrast, no significant correlations were found between organic parameters and heavy metals (r_s = –0.24 to –0.15, $p > 0.05$). This absence of statistical association confirms that organic and metal pollutants originate from distinct industrial sources and follow separate treatment pathways: organics are primarily removed via biodegradation and adsorption, whereas metals require precipitation, coagulation, or complexation [18]. Critically, this decoupling implies that compliance with organic parameters does not guarantee metal compliance, nor vice versa—regulators and plant operators must therefore monitor and manage both pollutant groups independently.

Interestingly, lead and chromium exhibited a strong positive correlation with each other (r_s = 0.78, $p < 0.05$), suggesting a shared industrial source. This may reflect the use of specific chrome-based azo dyes, metal-complex dyes, or fixing agents containing both metals, or alternatively, co-precipitation during chemical coagulation [18, 13]. The strong Pb–Cr cluster, isolated from the organic cluster, further reinforces the decoupling narrative. These correlation patterns are visualized in Figures 9 and 10, which present colour-coded heatmaps of the Spearman correlation matrix—clearly showing the tightly clustered organic–organic correlations, the isolated Pb–Cr correlation, and the complete absence of significant organic–metal linkages.

Table 5. Spearman correlation matrix (n=6 industries for organic parameters; n=5 for metals)

Parameter	BOD_5	COD	Color	TDS	pH	Pb	Cr
BOD_5	1.00	**0.94**	**0.83**	0.60	–0.34	–0.21	–0.18
COD	—	1.00	**0.86**	0.57	–0.29	–0.19	–0.15
Color	—	—	1.00	0.44	–0.41	–0.24	–0.22
TDS	—	—	—	1.00	–0.52	0.31	0.28
pH	—	—	—	—	1.00	0.12	0.09
Pb	—	—	—	—	—	1.00	**0.78**
Cr	—	—	—	—	—	—	1.00

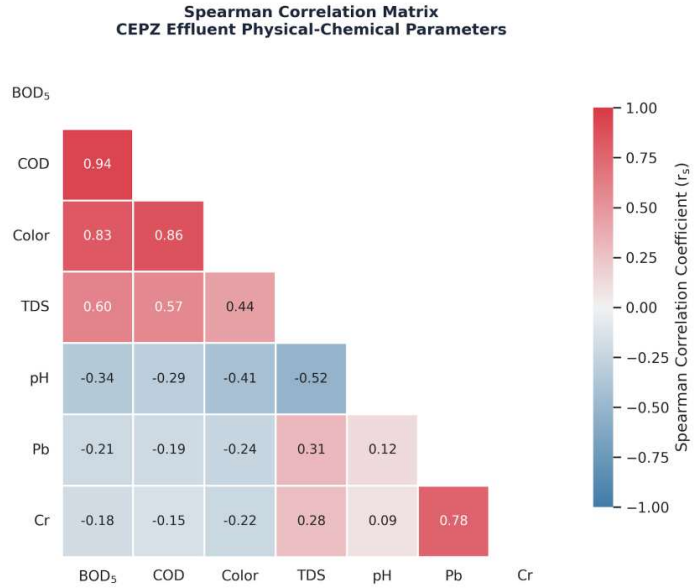


Figure 9. Spearman correlation heatmap for all parameters. Blue shades indicate positive correlations; red shades indicate negative correlations. The tightly clustered blue block among BOD_5, COD, and colour (r_s = 0.83–0.94) confirms shared organic sources. The isolated blue

block between Pb and Cr ($r_s = 0.78$) suggests a common industrial source for these metals. The pale/white shading between organic and metal parameters confirms the absence of significant organic–metal linkages (*$p > 0.05$ for all*).

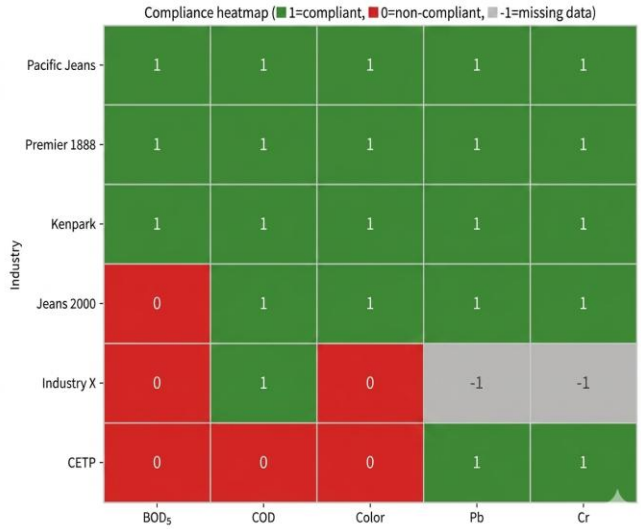


Figure 10. Pairwise scatter plot matrix (or alternative visualization) complementing the correlation heatmap, illustrating the strong linear relationships among BOD_5, COD, and colour, and the lack of any discernible trend between organics and metals.

4. Discussion

4.1 Decoupling is the central mechanistic finding

This study reveals a clear decoupling between organic and heavy metal pollution in CEPZ textile wastewater. Organic parameters (BOD_5, COD, colour) failed frequently, while lead and chromium were fully compliant across all industries. No statistical correlation existed between the two pollutant groups (Table 5, Figures 6–7). Mechanistically, this decoupling occurs because organic pollutants originate from dyes, sizing agents, and surfactants – used in large volumes and often refractory to biodegradation [19,20]. Heavy metals originate from specific metal-complex dyes or fixing agents. In CEPZ, either these are not used, or pre-treatment removes them effectively [16,17]. The decoupling observed here is mechanistically consistent with the chemistry of textile wastewater: organic pollutants are dominated by azo dyes and auxiliaries, while metals originate from specific metal-complex dyes or fixing agents. These are not necessarily co-emitted, and their removal pathways differ – biodegradation for organics vs. precipitation/coagulation for metals. The policy implication is that regulators and plant operators cannot assume that fixing organic pollution will fix metals, nor that metal compliance implies organic compliance. Separate monitoring, separate targets, and separate interventions are required [8].

4.2 CETP Failure is Chronic and Mechanistically Diagnosable

The CETP's non-compliance is unequivocally chronic rather than episodic, as corroborated by independent sampling events on two separate dates (Table 2, Figure 2) [9]. This repeated failure across multiple parameters provides a robust basis for mechanistic root-cause diagnosis, which can be deconstructed into three converging lines of evidence:

(1) **Biological overloading and recalcitrant breakthrough.** Consistently low removal efficiencies (BOD_5 48%, COD 55%, colour 20%) indicate that the existing biological stage is operating beyond its assimilative capacity. The poor overall performance aligns with broader evaluations of textile CETPs in Bangladesh [7], while the disproportionately low colour removal—relative to BOD_5/COD—confirms that recalcitrant dye compounds and refractory organics are bypassing degradation and exiting the system untreated [16].

(2) **Definitive hydraulic/biological instability (sludge washout).** The negative TSS removal efficiency (–36%) is unambiguous, direct evidence of solids loss from the secondary clarifier. This phenomenon is mechanistically attributable to either hydraulic overloading (exceeding the clarifier's surface overflow rate) or filamentous bulking (poor sludge settleability), both of which lead to the advection of active biomass out of the system. These chronic solids-management failures are consistent with industrial surveys of Bangladeshi textile sludge handling [9].

(3) **Regulatory threshold breaches.** The calculated exceedance factors—consistently above unity for BOD_5 (3.17), COD (1.20), and colour (1.27)—demonstrate that the CETP is acting as a net source of pollution, discharging loads that independently surpass the national discharge limits prescribed under the Environment Conservation Rules [20].

These quantitative findings are not isolated; they are directly validated by a parallel, independent assessment of the same CETP, which recorded identical BOD_5 removal (48%) and negative TSS removal (–36%) over the corresponding timeframe [1].

While these data confirm chronic failure, the reliance on discrete grab sampling for compliance monitoring introduces significant uncertainty, particularly given the high seasonal variability in effluent quality documented in Section 3.1 [3]. As critically evaluated in recent monitoring studies, grab samples provide only transient snapshots and are poorly suited for capturing dynamic diurnal or seasonal fluctuations, underscoring the urgent need for more robust monitoring frameworks, such as flow-proportional composite sampling or passive integrative samplers [25].

Given the mechanistic nature of the failure—specifically, the persistence of refractory colour and the instability of biological solids—the remedial pathway necessitates a tertiary polishing stage. Advanced oxidation processes (AOPs), including ozonation and Fenton's reagent, are mechanistically appropriate here because they specifically target the aromatic dye structures and recalcitrant organics that survive conventional secondary treatment. Indeed, a comprehensive review by Castellanos Henriquez et al. [32] confirmed that AOPs achieve maximum efficacy precisely when applied as a post-biological polishing step—exactly the configuration recommended for this CETP. Adsorptions via activated carbon or membrane filtration (NF/RO) are viable complementary options [33], though AOPs offer the added advantage of oxidative mineralization rather than mere phase transfer.

Finally, to prevent recurrent sludge washout, an immediate root-cause analysis (e.g., settling tests, microscopic examination of biomass, and hydraulic loading rate audits) is imperative.

Furthermore, the current infrequent grab-sampling regime must be replaced by a routine, transparent performance-auditing protocol that mandates monthly exceedance-factor (EF) reporting and enforces strict minimum removal-efficiency targets aligned with national standards, thereby enabling early detection of mechanistic deterioration before catastrophic failure occurs [5, 20].

4.3 Pacific Jeans provides a mechanistic benchmark for excellence

Pacific Jeans achieved removal efficiencies above 88% for all parameters and EF $\ll 1$ (Table 3, Figures 3–4). This proves that excellent treatment is technically achievable in the same industrial zone [27]. Success factors include consistent influent quality, adequate hydraulic retention time, effective aeration control, proper sludge management, and possibly tertiary polishing [2,31]. Pacific Jeans and Premier 1888 should serve as operational benchmarks for other industries and for the CETP operator [18].

4.4 Strong organic correlations support integrated polishing

The strong positive correlations among BOD_5, COD, and colour (r_s = 0.83–0.94, Table 5, Figures 6–7) are mechanistically significant. Azo dyes are chromophoric and also exert oxygen demand; their partial biodegradation consumes oxygen while leaving coloured intermediates [14]. Sizing agents and surfactants are colourless but have high COD and low biodegradability [15]. The implication is that integrated polishing – adsorption or advanced oxidation – will simultaneously reduce colour, COD, and BOD_5. This is more cost-effective than addressing each parameter separately [8]. The feasibility of such integrated strategies is further supported by recent advances in membrane technology. Sun et al. [41] developed a porous graphene oxide (PGO) membrane that achieved outstanding dye/salt separation under gravity-driven conditions, offering a promising tertiary treatment option for the CETP. The CETP could adopt such technologies sequentially – first adsorption/ozonation for colour and COD, then membrane filtration for TDS and trace metals.

4.5 Metal correlations and absence of organic–metal links

The strong lead–chromium correlation (r_s = 0.78, Table 5) suggests a shared industrial source. This relationship is visualized in Figure 6, which shows a linear clustering of Pb and Cr concentrations across the five facilities, with Kenpark exhibiting the highest Cr (0.080 mg L^{-1}) and Premier 1888 showing detectable but low levels of both metals [23]. Co-precipitation during chemical coagulation may also contribute [17]. The absence of correlation between organic parameters and metals confirms that different treatment pathways are needed. Biodegradation and adsorption remove organics; precipitation, coagulation, and complexation remove metals [16]. A well-designed ETP must address both pathways, but the CETP currently addresses neither adequately for organics, while metals are inadvertently controlled [18].

4.6 Policy implications derived from mechanistic analysis

Based on the mechanistic findings, the following policy actions are recommended for regulators, industry operators, and future research:

a) For regulators (BEPZA, DoE):

- Shift from pass/fail to performance-based compliance metrics. Use exceedance factors (EF), removal efficiency percentiles, and compliance scores (0–5) instead of single-parameter limits.
- Mandate routine heavy metal monitoring (Pb, Cr at minimum) for all textile ETPs and the CETP. Add chromium speciation (Cr(VI) vs. Cr(III)) to identify toxic hexavalent chromium, which is 100 times more toxic than Cr(III) [23].
- Enforce tertiary polishing at the CETP – activated carbon adsorption, ozonation, or membrane filtration. Require a root-cause analysis of sludge washout (hydraulic overloading, bulking).
- Establish a benchmarking program using Pacific Jeans and Premier 1888 as operational models. Publish annual compliance rankings to incentivize improvement.
- Replace infrequent grab sampling with monthly composite sampling and unannounced inspections for the CETP.

b) For industry operators (individual ETPs):

- Optimize aeration and hydraulic retention time where BOD_5 exceeds the limit (Jeans 2000, Industry X).
- Install tertiary polishing (coagulation-flocculation or adsorption) if colour or COD remain high.
- Maintain regular sludge management to prevent washout and negative TSS removal.
- Document and share best practices. Pacific Jeans achieved BOD_5 10 mg L^{-1}, COD 27 mg L^{-1}, colour 9 Pt-Co – study and replicate their operations.

c) For future research:

- Collect ≥3 temporal replicates per industry over four seasons (total n ≥72) to capture variability [32].
- Perform chromium speciation (Cr(VI) vs. Cr(III)) using IC-ICP-MS or a colorimetric method (USEPA Method 218.6).
- Include ecotoxicity bioassays (e.g., *Daphnia magna*, Microtox) to assess biological impact of the effluent mixture.
- Measure flow rates and calculate mass loads (kg/day) for BOD_5, COD, colour, Pb, and Cr to prioritize interventions.
- Conduct a cost-benefit analysis of CETP upgrades (activated carbon, ozonation, membrane filtration) to guide large-scale investments.

d) Immediate policy actions (next 6 months):

- Issue a directive to the CETP operator to submit a root-cause analysis and tertiary upgrade plan within 90 days.
- Publish a compliance scorecard (as in Table 4) for all textile industries in CEPZ annually.
- Train laboratory staff on chromium speciation methods and QA/QC protocols (field blanks, duplicates, spikes).
- Allocate funds for a 12-month monitoring study with temporal replicates – the present findings are screening-level only.

Figure 11 presents an actionable policy roadmap and engineering interventions for CEPZ wastewater remediation.

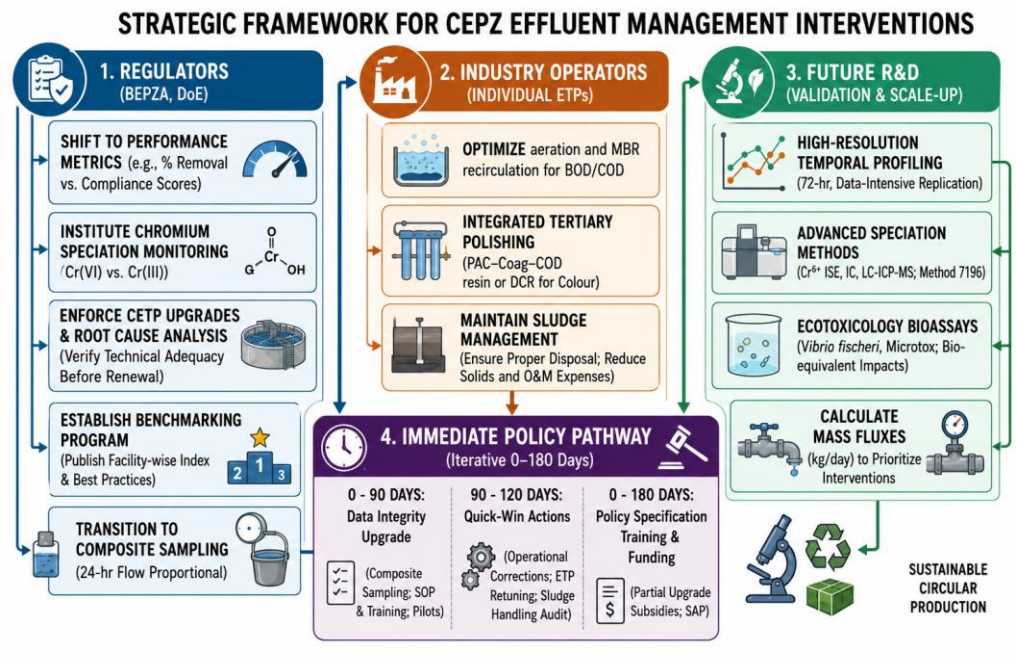


Figure 11: Actionable policy roadmap and engineering interventions for CEPZ wastewater remediation. A structured framework dividing short- and long-term actions for environmental regulators, private facility managers, and researchers. The schema emphasizes immediate engineering rectifications for centralized treatment failures, advanced chromium speciation tracking (Cr(VI) vs.Cr(III)), and introduces a 180-day countdown for institutional policy enforcement and standardized laboratory compliance training.

5. Study Limitations

Several limitations should be acknowledged. First, single grab samples (n = 1 per industry) cannot capture temporal variability [32]. Second, chromium speciation was not performed; total chromium compliance does not guarantee safety, as Cr(VI) is far more toxic than Cr(III) [23]. Third, data gaps exist (Industry X – no metals; September CETP – no metals, TDS, TSS). Fourth, correlations are exploratory due to small sample size. Fifth, the findings are specific to CEPZ and may not be transferable to other EPZs without recalibration. Sixth, removal efficiencies for the CETP are based on influent data provided by the operator, which may have its own uncertainties. Seventh, the study did not assess emerging contaminants such as microplastics or pharmaceuticals. Future work must include at least three temporal replicates per industry, chromium speciation (HPLC-ICP-MS), ecotoxicity assays (*Daphnia magna*), and seasonal sampling [8,32]. Additionally, the removal efficiency of emerging micro pollutants such as microfibers in CETPs and individual ETPs should be assessed, as studies have shown variable performance in Bangladeshi textile ETPs [11].

6. Conclusion

This screening-level study (single grab sample per facility; n = 1) provides the first integrated assessment of organic and heavy metal compliance in textile wastewater from the Chattogram Export Processing Zone (CEPZ), Bangladesh. The principal finding is a clear decoupling between organic and heavy metal pollution. Organic parameters (BOD_5, COD, and colour)

frequently exceeded ECR 2023 limits, whereas Pb and Cr remained compliant across all facilities, with negligible organic–metal correlations. Strong correlations among BOD_5, COD, and colour confirm common sources—namely, refractory dyes, sizing agents, and surfactants—supporting integrated tertiary polishing strategies. In contrast, the significant Pb–Cr correlation suggests a distinct industrial source for these metals, further reinforcing the decoupling narrative.

The CETP consistently exhibited poor organic treatment performance due to severe influent overloading and biological instability, evidenced by negative TSS removal indicating sludge washout and hydraulic failure. Conversely, Pacific Jeans achieved >88% removal for all monitored parameters and full compliance with ECR 2023 discharge limits, demonstrating that effective treatment is technically achievable within the same industrial zone.

These findings suggest that regulatory authorities should prioritize tertiary treatment upgrades at the CETP, accompanied by root-cause investigations of sludge washout and process instability. Monitoring programs could be strengthened by incorporating performance-based metrics—such as exceedance factors, removal efficiencies, and composite compliance indices—alongside routine monitoring of Pb and Cr, including chromium speciation where feasible.

Owing to the reliance on single grab samples (n = 1 per facility), the findings of this screening-level study are inherently exploratory and must be interpreted as hypothesis-generating rather than definitive. Rigorous validation will require future investigations incorporating seasonal-temporal replication (≥3 replicates per season), flow-proportional composite sampling, chromium speciation (Cr(VI) vs. Cr(III)), and ecotoxicological bioassays (e.g., *Daphnia magna*). Nevertheless, this study provides a robust, evidence-based framework for immediate regulatory and operational action. It prioritizes CETP upgrades, establishes operational benchmarks, and promotes a transition toward performance-based compliance metrics to safeguard the Karnaphuli River ecosystem and protect downstream communities that depend on its water resources.

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Data Availability Statement

All data generated or analyzed during this study are included in this published article and its supplementary information files.

Author Contributions

Muhammad Saidur Rahman: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Project administration, Resources.
Sabbir Ahmed: Investigation, Validation, Resources, Writing – review & editing, Quality assurance.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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