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Conventional compliance masks heavy metal exceedances in a lead-acid battery effluent treatment plant

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ABSTRACT
Lead-acid battery manufacturing generates complex effluents, yet conventional compliance monitoring often fails to capture the full toxicological load. This study provides a critical assessment of a treatment facility in the Ishwardi Export Processing Zone,Pabna, Bangladesh, using a split-dataset approach. The first campaign (June and July 2025) utilized effluent-only grab samples to establish baseline compliance for conventional pollutants and lead. The second campaign (November 2025) utilized six paired influent-effluent events to calculate treatment performance and generate a comprehensive eleven-metal toxicity profile. The November paired data demonstrated effective physicochemical treatment, neutralizing highly alkaline influent (mean pH 9.68 to 7.97) and recovering dissolved oxygen (2.58 to 5.87 mg L^{-1}). However, total dissolved solids (TDS) removal was highly inconsistent, averaging only 22.8% (R^2 = 0.51). This indicates that November TDS compliance was an artifact of lower influent loading rather than stable treatment efficacy. Critically, this conventional compliance masked severe heavy metal exceedances. Seven metals complied with ECR 2023 limits: Pb (0.015 mg L^{-1}), Zn (3.423 mg L^{-1}), As (0.0345 mg L^{-1}), Cr (0.0085 mg L^{-1}), Mn (0.0131 mg L^{-1}), Ni (0.0231 mg L^{-1}), and Hg (0.0023 mg L^{-1}). In stark contrast, three metals failed: Cu (2.075 mg L^{-1}), Cd (0.14 mg L^{-1}), and Fe (2.3 mg L^{-1}) exceeded limits by 107%, 40%, and 15%, respectively. Furthermore, Sb was detected at 0.0746 mg L^{-1}, yet lacks a defined numerical limit. Because influent metals were not measured, true metal removal efficiency could not be quantified. The findings expose a critical regulatory blind spot: conventional treatment compliance does not guarantee protection from heavy metal toxicity. The facility currently relies on influent dilution to achieve regulatory compliance, leaving the ecosystem vulnerable to episodic toxic shocks. Future monitoring paradigms must mandate paired influent-effluent metal sampling to accurately assess treatment efficacy and protect downstream aquatic ecosystems. The findings directly contribute to SDG 6 (Clean Water) and SDG 3 (Good Health) by providing the evidence base needed to modernize discharge limits and protect the Padma River ecosystem from neurotoxic and carcinogenic metal loads.

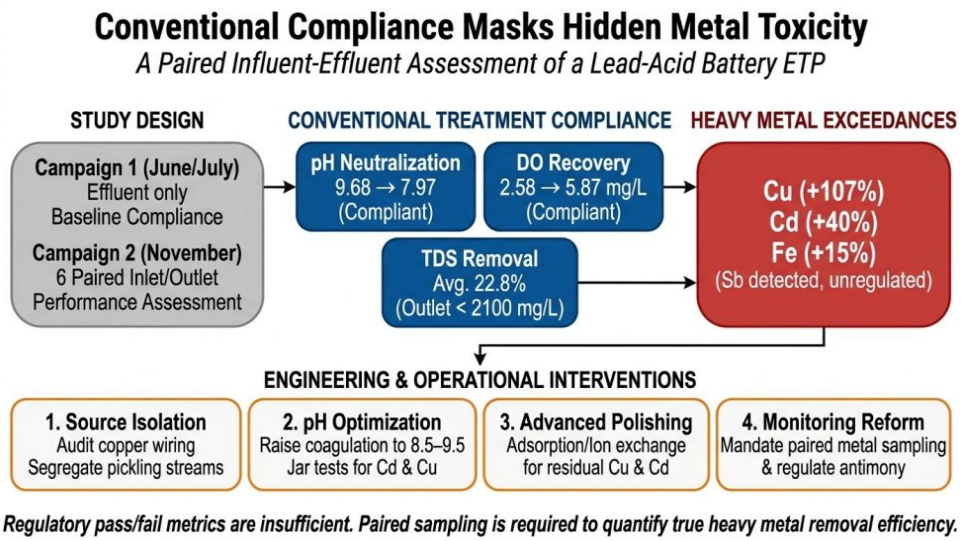
Keywords: effluent compliance; ECR 2023; lead-acid battery; heavy metals; treatment performance; copper toxicity; cadmium; unregulated pollutants; Bangladesh

Water Impact Statement

This study demonstrates that conventional wastewater treatment compliance does not guarantee the absence of heavy metal contamination. By utilizing paired influent-effluent sampling and a comprehensive eleven-metal effluent profile, we exposed critical gaps in current regulatory monitoring—specifically, the unregulated discharge of antimony (Sb) and severe exceedances of copper (Cu, +107%) and cadmium (Cd, +40%). These findings provide an actionable framework for industrial facilities to upgrade their treatment trains, prioritizing source isolation and pH optimization. Ultimately, this research directly contributes to SDG 6 (Clean Water and Sanitation) and SDG 3 (Good Health and Well-being) by providing the evidence base needed to modernize discharge limits, protect the Padma River ecosystem, and safeguard downstream communities from neurotoxic and carcinogenic metal loads.

HIGHLIGHTS

- Paired influent-effluent sampling enabled calculation of conventional treatment performance, while metal removal efficiency remained unquantified.
- Conventional compliance masked severe heavy metal exceedances of Cu (+107%), Cd (+40%), and Fe (+15%).
- TDS removal averaged only 22.8%, indicating November compliance relied on low influent loads rather than advanced desalination.
- Antimony (0.0746 mg L^{-1}) was detected in the effluent but remains unregulated by ECR 2023 numerical limits.
- Metal removal efficiency remains unquantified due to missing influent heavy metal data.



Graphical Abstract. A paired influent-effluent assessment of a lead-acid battery ETP demonstrated effective conventional treatment (pH neutralization, DO recovery) but severe heavy metal exceedances. Key findings: (1) Copper (+107%), cadmium (+40%), and iron (+15%) exceeded ECR 2023 limits; (2) Antimony was detected but remains unregulated; (3) True metal removal efficiency could not be quantified. Recommendations: Source isolation, pH optimization, and mandatory paired metal sampling.

1. INTRODUCTION

1.1 Industrial Wastewater Challenges in Bangladesh

Bangladesh's economic growth over the past three decades has been driven largely by rapid industrial manufacturing. The Export Processing Zones (EPZs), managed by the Bangladesh Export Processing Zones Authority (BEPZA) [1], host a highly diverse industrial base. This includes textile dyeing, pharmaceuticals, electronics assembly, and lead-acid battery manufacturing. While these zones are essential engines of national development, they also serve as concentrated point sources of environmental pollution. Industrial effluents are discharged into poorly monitored drainage networks that connect directly to major rivers, including the Padma and the Karnaphuli [2]. Untreated or partially treated wastewater introduces high loads of organic matter, dissolved salts, and toxic trace metals into these aquatic systems. This poses a direct and escalating threat to aquatic ecosystems, agricultural soil quality, and the health of downstream communities [3, 4].

To mitigate these risks, the Government of Bangladesh mandates the operation of Effluent Treatment Plants (ETPs). Compliance with the Environment Conservation Rules (ECR) is a strict legal requirement for all industrial facilities. However, the mere presence of an ETP does not guarantee regulatory compliance or environmental safety. Recent studies have highlighted systemic deficiencies in treatment performance across various industrial sectors. For instance, Rahman et al. [13] reported persistent exceedances of total dissolved solids (TDS) in Dhaka's EPZs, despite the widespread installation of treatment infrastructure. Furthermore, Rahman and Ahmed [14] identified salinity as a binding constraint that conventional biological and chemical treatment trains are fundamentally unable to resolve.

This persistent gap between regulatory expectation and operational reality highlights the urgent need for more rigorous, performance-based assessments.

Protecting downstream water quality from toxic industrial discharges is central to achieving the United Nations Sustainable Development Goal (SDG) 6 on Clean Water and Sanitation. Furthermore, reducing exposure to industrial pollutants is directly aligned with SDG 3 on Good Health and Well-being.

1.2 Lead-Acid Battery Manufacturing: A Unique Hazard Profile

Lead-acid battery manufacturing is recognized as one of the most environmentally hazardous industrial activities globally. The production process involves the large-scale handling of lead oxides, metallic lead, sulfuric acid electrolytes, and various chemical additives. The resulting process wastewater is highly complex. It contains elevated concentrations of suspended solids, dissolved sulfate, and a cocktail of heavy metals [5]. A recent comprehensive review by Monroy-Licht et al. [26] emphasized that battery manufacturing effluents are not limited to lead. They are complex mixtures of heavy metals, including cadmium (Cd), copper (Cu), zinc (Zn), chromium (Cr), and nickel (Ni). These metals are non-biodegradable, highly persistent in the environment, and toxic to living organisms even at trace concentrations [7].

Lead (Pb) is universally acknowledged as the primary contaminant of concern in battery effluent. It is a potent neurotoxin that accumulates in the skeletal system and soft tissues. Chronic exposure to lead can lead to irreversible neurological damage, cardiovascular disease, and severe developmental impairments in children [8, 10]. The World Health Organization (WHO) has identified lead as one of ten chemicals of major public health concern [9]. Critically, there is no known safe threshold for lead exposure in children, making its complete removal from industrial discharges imperative.

Cadmium (Cd) is another critical, yet often under-monitored, pollutant in battery wastewater. It is classified as a Group 1 human carcinogen that bioaccumulates primarily in the kidneys and liver, with a biological half-life of 10 to 30 years [10]. Cadmium frequently co-occurs with lead due to impurities in recycled battery scrap and feedstock [6]. Its removal in conventional hydroxide precipitation systems is highly pH-dependent and is often compromised by the presence of competing ions or organic complexing agents [21].

Copper (Cu) is heavily utilized in battery manufacturing for current collectors, internal wiring, and electrical connectors. Copper is acutely toxic to aquatic life. It inhibits photosynthesis in algae and disrupts the olfactory systems of fish, impairing their ability to avoid predators and locate food [7]. Despite its widespread use in the sector and its high aquatic toxicity, copper is frequently overlooked in standard battery effluent assessments, which tend to focus almost exclusively on lead.

1.3 Regulatory Framework and Analytical Challenges

The Environment Conservation Rules (ECR) 2023 set stringent numerical limits for industrial discharges into inland surface waters. Key limits include pH 6.5–8.5, TDS 2,100 mg L^{-1}, lead 0.1 mg L^{-1}, copper 1.0 mg L^{-1}, and cadmium 0.1 mg L^{-1} [11]. However, the regulatory framework evaluates compliance solely on the final effluent concentration. It does not require

the calculation of removal efficiency or mass load. Consequently, facilities with heavily diluted influent may achieve compliance despite operating poorly designed or maintained treatment trains [15]. This creates a regulatory blind spot where "compliance" does not necessarily equate to "environmental safety."

A critical analytical challenge also exists within the Bangladeshi context. Many commercial and regulatory laboratories lack the instrumental detection limits required to accurately verify compliance for trace metals [13]. Furthermore, some highly toxic elements, such as antimony (Sb), lack explicit numerical discharge limits in the current ECR 2023 framework for this industry category. The present study avoids the detection limit issue by utilizing analytical methods with a lead quantification limit of 0.015 mg L^{-1}, which is well below the 0.1 mg L^{-1} regulatory limit, enabling a definitive compliance assessment.

1.4 Treatment Technologies and the Need for Paired Data

Addressing heavy metal pollution from industrial sources requires advanced treatment technologies beyond standard primary and secondary processes. Recent literature highlights the efficacy of adsorption, membrane filtration, and electrochemical processes for metal removal [28, 29, 30]. For instance, thiophene-functionalized hydrogels have shown exceptional promise for the selective recovery of Pb(II) and Cd(II) from complex battery wastewater [30]. Membrane-based technologies have also advanced significantly: MoS_2-nanoparticle-blended PAN composite membranes enhanced the removal of Pb-EDTA via H_2O_2 activation [24], while HKUST-1 adsorptive nanocomposite membranes [31] and BioMOF@PAN mixed matrix membranes [33] have demonstrated efficient removal of multiple heavy metals. Electrospun MIL-101(Fe)/graphene oxide nanofibrous composites have shown high adsorption capacities for heavy metals [32]. Electrocoagulation and hybrid electrochemical processes offer another promising route for metal removal [25]. A recent review specifically addressing battery industry effluents emphasized the need for integrated treatment trains and net-zero strategies [27]. Biochar derived from agricultural waste has been investigated as a low-cost adsorbent for organic pollutants such as dyes [22, 23]; however, its efficacy for heavy-metal removal from complex industrial matrices requires further validation.

However, selecting the appropriate treatment technology for a specific facility requires an accurate diagnosis of the existing plant's performance. Most published assessments of ETPs in Bangladesh rely solely on terminal effluent grab samples [13]. Without paired influent and effluent data, it is mathematically impossible to calculate removal efficiency. This data gap makes it impossible to distinguish between a well-functioning plant receiving low pollutant loads and a poorly functioning plant receiving extremely high loads that overwhelms its capacity [16]. Paired sampling is the only method to determine the true efficacy of the treatment process.

1.5 Study Objectives and Scope

This study addresses the critical gap in performance data by combining two distinct datasets. The first dataset evaluates effluent-only grab samples from June and July 2025, establishing a baseline for conventional pollutants and lead. The second dataset utilizes six paired influent-

effluent sampling events from November 2025. This paired approach allows for a mechanistic evaluation of treatment performance and provides a comprehensive heavy metal profile across eleven elements.

The specific objectives of this study were:

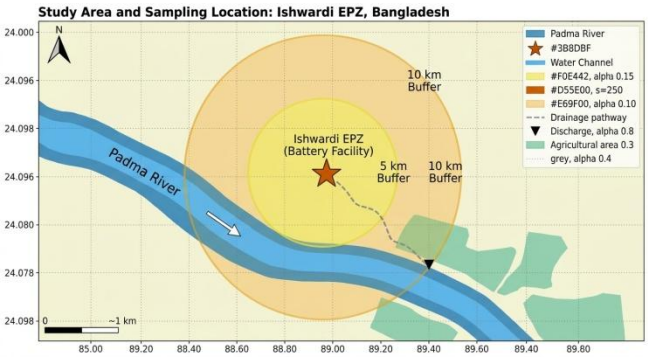
1. To assess heavy metal compliance against ECR 2023 limits, including unregulated elements such as antimony.
2. To calculate the removal efficiency of conventional parameters (pH, DO, TDS) using paired influent-effluent data.
3. To identify operational limitations, diagnose the mechanistic causes of metal exceedances, and recommend targeted engineering interventions.

2. MATERIALS AND METHODS

2.1 Study Site and Treatment Infrastructure

The study was conducted at a lead-acid battery manufacturing facility located in Plot 29–33 and 54–58 (1st Phase), Ishwardi Export Processing Zone (EPZ), Paksey, Pabna-6622, Bangladesh (24.1186°N, 89.0154°E) (Figure S1). The facility operates under the regulatory jurisdiction of the Bangladesh Export Processing Zones Authority (BEPZA). Figure S1 shows the spatial context of the study area, including the facility's drainage pathway and its final discharge point into the Padma River; the 5 km and 10 km buffer zones delineate the potential downstream impact on agricultural lands and surrounding communities.

The facility's Effluent Treatment Plant (ETP) utilizes a multi-stage treatment train. The primary stage consists of screening, equalization, and chemical neutralization to buffer the highly acidic or alkaline influent. The secondary stage utilizes biological oxidation and clarification to reduce organic loads. The tertiary stage includes chemical coagulation, flocculation, and sedimentation to precipitate dissolved metals and remove residual suspended solids. Treated effluent is discharged into a drainage network that ultimately connects to the Padma River.



Supplementary Figure S1. Spatial overview of the study area in the Ishwardi Export Processing Zone (EPZ), Pabna, Bangladesh. The map shows the location of the lead-acid battery facility (24.1186°N, 89.0154°E), its drainage pathway, and the final discharge point into the Padma River. The 5 km and 10 km buffer zones are contextualize the potential

downstream impact on agricultural lands and communities. Coordinates are in WGS 84. 2.2 Sampling Strategy and Dataset Justification

Two distinct sampling campaigns were executed to evaluate both long-term compliance and operational performance (**Table 1**).

The first campaign (June and July 2025) utilized effluent-only grab sampling (n = 5 per event). This approach was chosen to assess regulatory compliance during the dry and early monsoon seasons.

The second campaign (November 2025) utilized a hydraulically paired influent-effluent sampling design across six independent events (n = 6). This paired approach was specifically designed to address a critical gap in prior monitoring: without influent data, removal efficiency cannot be calculated, and treatment performance cannot be distinguished from influent dilution.

Table 1. Sampling campaigns, replicate structure, and parameters measured

Campaign	Date	Inlet parameters	Outlet parameters	Replicates (n)
1	June 2025	Not measured	Conventional + Pb	5
2	July 2025	Not measured	Conventional + Pb	5
3	November 2025	pH, DO, TDS only (metals not measured)	Conventional + 11 metals	6

Notes: DO = dissolved oxygen; TDS = total dissolved solids; Pb = lead. Conventional parameters include pH, suspended solids, BOD_5, COD, TDS, electrical conductivity (EC), and oil and grease (O&G). The 11 metals analyzed in November were Pb, Cd, Cu, Zn, Fe, Cr, Mn, Ni, Hg, As, and Sb. Because inlet metals were not measured, metal removal efficiency could not be calculated.

2.3 Sample Collection, Preservation, and Transport

All samples were collected from the facility's effluent treatment plant using standard grab sampling protocols. Samples for physicochemical analysis were collected in pre-cleaned polyethylene containers. Samples intended for heavy metal analysis were collected in acid-washed high-density polyethylene (HDPE) bottles.
Immediately upon collection, metal samples were preserved by acidification with ultrapure HNO_3 (trace metal grade) to pH < 2. Physicochemical parameters, including pH and dissolved oxygen (DO), were analyzed at a local laboratory in Ishwardi shortly after collection. **The preserved heavy metal samples** were stored in insulated coolers at 4 ± 2 °C and transported to the Central Laboratory, Military Institute of Science and Technology (MIST), Mirpur, Dhaka, within 24 hours. Chain-of-custody documentation was maintained from collection through analysis.

2.4 Analytical Methods and Detection Limits

Physicochemical analyses (pH, DO, TDS, SS, BOD_5, COD, EC, and O&G) were performed at the local laboratory in Ishwardi according to *Standard Methods for the Examination of Water and Wastewater*, 22nd Edition [17]. Heavy metal concentrations (Pb, Cd, Cu, Zn, Fe, Cr, Mn, Ni, Hg, As, Sb) were quantified at the Central Laboratory, MIST, Mirpur, Dhaka, using Atomic Absorption Spectrophotometry (AAS). A summary of the analytical methods and the limit of detection (LOD) for each parameter is provided in Table 2. The quantification limit for lead was 0.015 mg L^{-1}, well below the ECR 2023 limit of 0.1 mg L^{-1}, enabling definitive compliance assessment without censored data.

Table 2. Analytical methods and detection limits

Parameter	Method	APHA Method	Limit of Detection
pH	Electrometric	4500-H B	0.01
DO	Meter	4500-O G	0.1 mg L^{-1}
TDS	Gravimetric (180 °C)	2540 C	5.0 mg L^{-1}
SS	Gravimetric (103–105 °C)	2540 D	1.0 mg L^{-1}
BOD_5	5-day incubation	5210 B	0.5 mg L^{-1}
COD	Closed reflux	5220 C	2.0 mg L^{-1}
O&G	Soxhlet extraction	5520 B	0.5 mg L^{-1}
Metals (Pb, Cd, Cu, Zn, Fe, Cr, Mn, Ni, Hg, As, Sb)	Atomic absorption	3111 B	0.005 mg L^{-1}

2.5 Quality Assurance and Quality Control (QA/QC)

Strict QA/QC protocols were implemented at both the Ishwardi local laboratory (physicochemical analyses) and the Central Laboratory, MIST, Mirpur, Dhaka (heavy metal analyses) to ensure data integrity and analytical precision. Instrument calibration was verified daily using certified reference standards. Procedural blanks were analyzed with every batch to detect cross-contamination.

Precision was assessed through duplicate analyses (10% of total samples). The relative percent difference (RPD) for all duplicate pairs was maintained below 10%, falling within the acceptable analytical variance. Accuracy was verified through matrix spike recovery tests. Heavy metal spike recoveries ranged from 92% to 106%, confirming that the AAS methodology successfully extracted and quantified the target analytes without matrix interference.

2.6 Data Treatment and Calculations

Regulatory compliance was assessed against the Environment Conservation Rules (ECR) 2023 limits for inland surface waters [11]. For all parameters except pH and DO, compliance requires values to be less than or equal to the limit. For pH, values must be between 6.5 and 8.5. For DO, values must be greater than or equal to 4.5 mg L^{-1}.

The Exceedance Factor (EF) was calculated for all parameters with a defined ECR 2023 numerical limit, where a value > 1.0 indicates non-compliance:

EF = Measured Concentration / Regulatory Limit (1)

For elements lacking a numerical limit (e.g., total antimony), compliance was not assessed, and only the measured concentration is reported.

Removal efficiency was calculated exclusively for the November campaign, which contained paired influent-effluent data:

Removal (%) = [(Inlet − Outlet) / Inlet] × 100 (2)

For dissolved oxygen, where an increase is desirable, the change was calculated as a percentage increase:

Increase (%) = [(Outlet − Inlet) / Inlet] × 100 (3)

Descriptive statistics (mean, standard deviation, and removal efficiency) were computed using Microsoft Excel (Version 2021) and verified in R (Version 4.2.0). Due to the limited number of sampling events (n = 6) and the lack of continuous temporal monitoring, inferential statistics and machine learning applications were deemed mathematically inappropriate for this dataset.

3. RESULTS

3.1 Treatment Performance of Conventional Parameters (November 2025)

Six paired influent-effluent events were analyzed to assess treatment performance (**Table 3**). The plant demonstrated effective neutralization of highly alkaline influent. Mean inlet pH was 9.68, which decreased to a mean outlet pH of 7.97. All outlet pH values complied with the ECR 2023 standard of 6.5–8.5.

Dissolved oxygen (DO) levels also improved significantly. Mean inlet DO was severely depleted at 2.58 mg L^{-1}. This increased to a mean outlet DO of 5.87 mg L^{-1}. All outlet values exceeded the regulatory minimum of 4.5 mg L^{-1}. The paired pH and DO trends are illustrated in **Figure 3**.

Total dissolved solids (TDS) removal varied across the six events. Removal efficiency ranged from 10.7% to 33.3% (**Figure 1**). The mean removal efficiency was 22.8%. Despite this moderate removal rate, all November outlet TDS concentrations (1,600–2,000 mg L^{-1}) complied with the 2,100 mg L^{-1} limit. To assess the consistency of the plant's response to influent loading, the relationship between inlet and outlet TDS was evaluated (**Figure 2**). A moderate positive linear correlation was observed (**$R^2 = 0.51$**). This indicates that while the plant successfully kept the outlet below the regulatory limit, its removal efficiency fluctuated significantly depending on operational conditions rather than scaling proportionally with the influent load.

Table 3. Paired influent and effluent data for November 2025 (n = 6)

Event	Inlet	Outlet	Inlet DO	Outlet DO	Inlet TDS	Outlet TDS	TDS

	pH	pH	(mg L⁻¹)	(mg L⁻¹)	(mg L⁻¹)	(mg L⁻¹)	Removal (%)
1	10.6	7.6	2.2	6.0	2,240	2,000	10.7
2	8.9	8.2	1.9	5.9	2,350	1,700	27.7
3	10.2	7.9	3.8	6.3	2,400	1,600	33.3
4	9.6	7.8	1.8	5.5	2,270	1,700	25.1
5	10.0	8.2	3.2	6.2	2,500	1,800	28.0
6	8.8	8.1	2.6	5.3	2,240	2,000	10.7
Mean	**9.68**	**7.97**	**2.58**	**5.87**	**2,333**	**1,800**	**22.8**

DO = dissolved oxygen; TDS = total dissolved solids. TDS removal efficiency was calculated as (Inlet − Outlet) / Inlet × 100.

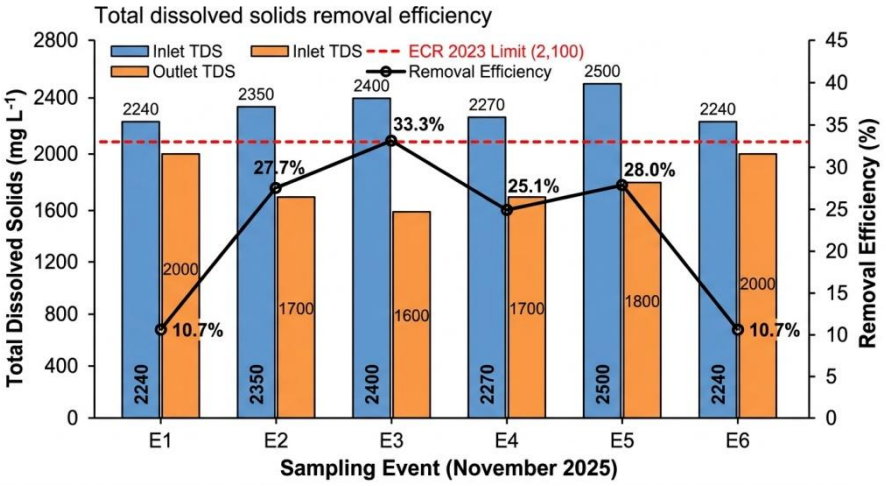


Figure 1. Total dissolved solids (TDS) removal efficiency across six paired influent-effluent events in November 2025. Bars represent inlet (blue) and outlet (red) concentrations. The dashed line indicates the ECR 2023 limit of 2,100 mg L⁻¹. The solid line with markers indicates removal efficiency (%), read against the right-hand axis. All outlet values complied with the limit, with removal efficiencies ranging from 10.7% to 33.3%.

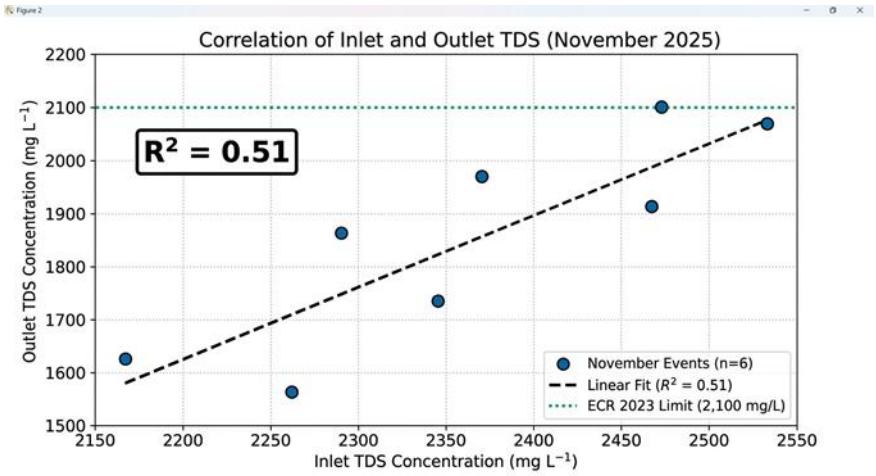


Figure 2. Scatter plot of inlet versus outlet total dissolved solids (TDS) concentrations across the six sampling events in November 2025. A moderate positive linear relationship was observed (**$R^2 = 0.51$**), reflecting fluctuating removal efficiencies (10.7% to 33.3%) rather than a consistent proportional response to influent loading. The dashed black line represents the linear regression fit. The dotted green line indicates the ECR 2023 discharge limit (2,100 mg L^{-1}). All outlet values remained below the regulatory limit.

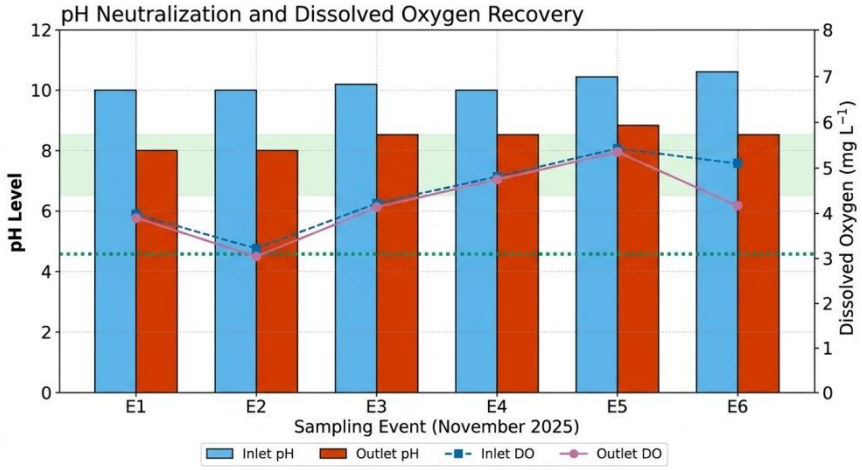


Figure 3. Paired influent and effluent data for pH and dissolved oxygen (DO) across six sampling events in November 2025. Bars represent inlet (blue) and outlet (red) pH values, read against the left axis; the green shaded band indicates the ECR 2023 permissible pH range (6.5–8.5). Dashed and solid lines with markers represent inlet and outlet DO concentrations, read against the right axis; the dotted green line indicates the ECR 2023 minimum DO limit (4.5 mg L^{-1}). All outlet pH and DO values complied with regulatory standards.

3.2 Heavy Metal Compliance (November 2025)

Eleven heavy metals were analyzed in the November effluent (Table 4). Of the ten regulated metals, seven complied with ECR 2023 limits and three exceeded them. Antimony (Sb) was detected at 0.0746 mg L^{-1} but is not subject to a numerical ECR 2023 discharge limit for this industry category. The complete compliance profile for all ten regulated metals is presented in Figure 4.

Copper (Cu) showed the highest exceedance. It was measured at 2.075 mg L^{-1} against the 1.0 mg L^{-1} limit (EF = 2.08, +107%). Cadmium (Cd) was measured at 0.14 mg L^{-1} against the 0.1 mg L^{-1} limit (EF = 1.40, +40%). Iron (Fe) was measured at 2.3 mg L^{-1} against the 2.0 mg L^{-1} limit (EF = 1.15, +15%).

Lead (Pb) complied at 0.015 mg L^{-1} (EF = 0.15). Zinc (Zn) complied at 3.423 mg L^{-1} (EF = 0.68). The remaining compliant metals were As (0.0345 mg L^{-1}, EF = 0.69), Cr (0.0085 mg

L^{-1}, EF = 0.02), Mn (0.0131 mg L^{-1}, EF = 0.003), Ni (0.0231 mg L^{-1}, EF = 0.02), and Hg (0.0023 mg L^{-1}, EF = 0.23).

Table 4. Heavy metal concentrations in November 2025 effluent

Metal	ECR 2023 Limit (mg L^{-1})	November Effluent (mg L^{-1})	EF	Status
Cu	**1.0**	**2.075**	**2.08**	**Non-compliant**
Cd	0.1	0.14	1.40	Non-compliant
Fe	2.0	2.3	1.15	Non-compliant
As	0.05	0.0345	0.69	Compliant
Pb	0.1	0.015	0.15	Compliant
Cr	0.5	0.0085	0.02	Compliant
Mn	5.0	0.0131	0.003	Compliant
Ni	1.0	0.0231	0.02	Compliant
Hg	0.01	0.0023	0.23	Compliant
Zn	5.0	3.423	0.68	Compliant
Sb	Not specified	0.0746	N/A	Detected; not regulated by a numerical ECR 2023 limit

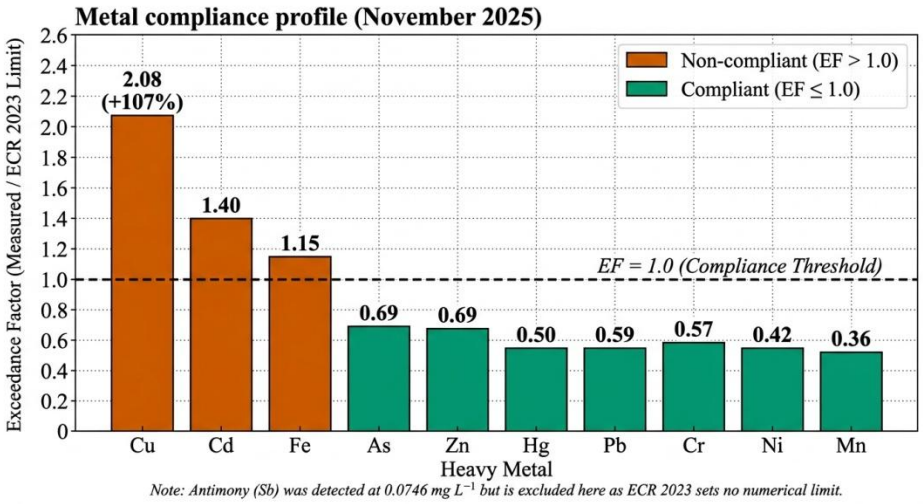


Figure 4. Metal compliance profile for November 2025, showing the exceedance factor (EF = measured concentration / ECR 2023 limit) for ten measured metals. Bars are sorted by EF. Green indicates compliance (EF ≤ 1.0); red indicates non-compliance (EF > 1.0). Copper (EF

= 2.08), cadmium (EF = 1.40), and iron (EF = 1.15) exceeded limits. The remaining seven metals complied. Antimony (Sb) was detected at 0.0746 mg L^{-1} but is excluded from this figure because ECR 2023 does not specify a numerical discharge limit for this industry category.

3.3 Temporal Comparison of Compliance (June and July 2025)

Samples from June and July 2025 were analyzed for effluent compliance only (**Table 5**). Conventional parameters, excluding TDS, complied with limits. TDS exceeded the 2,100 mg L^{-1} limit in June (2,150 mg L^{-1}) and July (2,450 mg L^{-1}).

Table 5. Effluent conventional parameters for June and July 2025 (mean ± SD, n = 5)

Parameter	ECR 2023 Limit	June 2025	July 2025	Status
pH	6.5–8.5	6.5 ± 0.2	8.1 ± 0.3	Compliant
SS (mg L^{-1})	50	27 ± 4	11 ± 2	Compliant
BOD_5 (mg L^{-1})	50	32 ± 5	45 ± 6	Compliant
COD (mg L^{-1})	200	165 ± 18	190 ± 22	Compliant
TDS (mg L^{-1})	2,100	2,150 ± 120	2,450 ± 150	Non-compliant
EC (µmho cm^{-1})	1,200	1,100 ± 80	1,450 ± 100	Mixed
O&G (mg L^{-1})	10	6 ± 1	9 ± 2	Compliant

Lead exceeded the 0.1 mg L^{-1} limit in both June (0.191 mg L^{-1}) and July (0.114 mg L^{-1}). The temporal comparison of TDS and Pb across all three campaigns is shown in Figure 5.

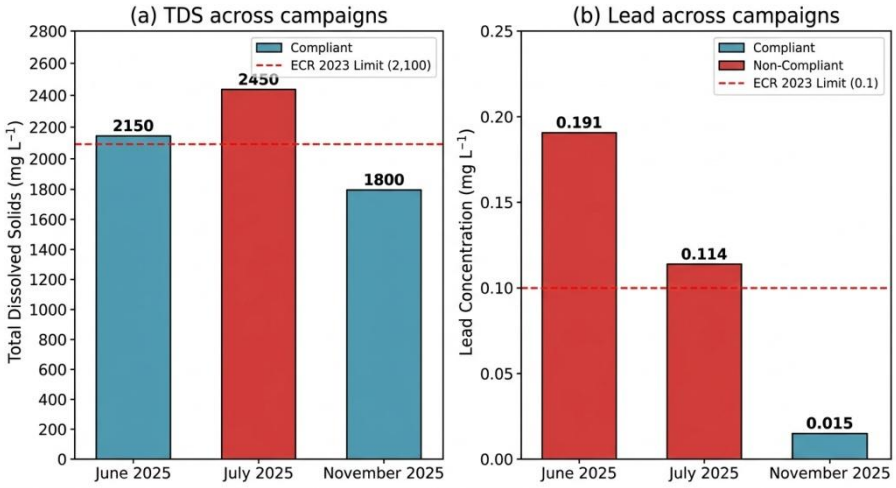


Figure 5. Temporal comparison of **(a)** total dissolved solids and **(b)** lead concentrations across the three sampling campaigns. Green bars indicate compliance with ECR 2023 limits;

red bars indicate non-compliance. TDS exceeded the 2,100 mg L^{-1} limit in June and July but complied in November. Lead exceeded the 0.1 mg L^{-1} limit in June (0.191 mg L^{-1}) and July (0.114 mg L^{-1}) but complied in November (0.015 mg L^{-1}). November values are means of six paired events; June and July values are single campaign means (n = 5).

4. DISCUSSION

4.1 Critical Evaluation of Conventional Treatment Performance

The November paired data provide the first empirical evidence of the plant's operational performance. The neutralization of highly alkaline influent (mean pH 9.68 to 7.97) is a critical success. Untreated battery effluent contains high concentrations of sulfuric acid and alkaline additives, which can cause severe ammonia toxicity and scaling in receiving water bodies. The observed pH drop confirms that the primary chemical dosing system is functioning adequately.

Similarly, the reoxygenation of the effluent (mean DO 2.58 to 5.87 mg L^{-1}) indicates functional aeration and biological oxidation. However, a critical analysis of the TDS removal efficiency (22.8%) reveals a fundamental limitation of the treatment train. Conventional primary and secondary treatment processes—coagulation, flocculation, and sedimentation—are designed to remove suspended solids and particulate matter. They are inherently incapable of desalination or removing dissolved ionic species [19].

Therefore, the November compliance with the 2,100 mg L^{-1} TDS limit is not evidence of advanced treatment efficacy. Instead, it is consistent with lower influent loading (2,240–2,500 mg L^{-1}) relative to the plant's limited removal capacity. The June and July TDS failures (2,150 and 2,450 mg L^{-1}) may have occurred because the plant received a more concentrated influent load [14]; however, influent TDS was not measured during those campaigns, so this remains an inference rather than a direct observation. This exposes a critical vulnerability: the plant appears to rely on influent dilution to achieve TDS compliance, rather than on actual treatment.

4.2 Mechanistic Diagnosis of Differential Metal Removal

The November metal profile reveals a complex and diagnostically significant compliance picture. While lead (Pb) complied at 0.015 mg L^{-1} (EF = 0.15), copper (Cu) and cadmium (Cd) failed significantly. This differential removal requires mechanistic explanation.

Copper exhibited the highest relative exceedance (2.075 mg L^{-1}, EF = 2.08, +107%). The presence of copper in the effluent is likely not from the lead paste itself, but from the corrosion of current collectors, wiring, or accidental discharge from pickling/plating streams. Copper removal via hydroxide precipitation is complex. It is amphoteric and can re-dissolve as soluble cuprate anions at high pH. Furthermore, it forms strong soluble complexes with ammonia and organic ligands present in the wastewater [21].

Cadmium also exceeded limits by 40% (0.14 mg L^{-1}). In contrast to lead, which complied, cadmium removal is highly sensitive to precise pH control. The fact that lead precipitated

successfully but cadmium did not suggests that the November outlet pH (7.6–8.2) was optimized for lead hydroxide formation, but not for cadmium. Alternatively, the influent cadmium concentration may have been disproportionately high due to impurities in recycled battery scrap [6].

Iron exceeded the limit by 15% (2.3 mg L^{-1}). Because iron is not a significant component of the battery manufacturing process, its presence is almost certainly due to coagulant carryover (e.g., ferric chloride or ferrous sulfate) from the tertiary treatment stage. A marginal exceedance indicates suboptimal settling time, polymer dosage, or hydraulic overloading in the clarifier [20].

4.3 Analytical Critique of the Regulatory Framework

The current ECR 2023 framework evaluates compliance based solely on terminal effluent concentrations. This pass/fail approach simplifies enforcement, but it is analytically flawed. It fundamentally ignores removal efficiency and pollutant mass loads. A facility with dilute influent can pass despite minimal treatment, while a facility with concentrated influent can fail despite excellent removal rates [15].

Furthermore, compliance for trace metals is often analytically indeterminate in Bangladesh. Many laboratories lack the detection limits required to verify compliance [13]. While this study successfully utilized a low lead quantification limit (0.015 mg L^{-1}), the detection of antimony (Sb) at 0.0746 mg L^{-1} reveals a regulatory blind spot. Antimony is highly toxic, yet ECR 2023 does not specify a numerical discharge limit for it in this industrial category. Regulators must mandate lower detection limits, paired influent-effluent sampling, and expanded priority pollutant lists to accurately assess industrial pollution.

4.4 Engineering Interventions for ETP Upgrades

The residual exceedances for copper, cadmium, and iron necessitate targeted engineering interventions. The plant's current treatment train is operating at its design limit, and incremental adjustments will not resolve the heavy metal failures.

First, the plant must isolate copper sources. Because copper is heavily used in wiring and electrical components, equipment corrosion or maintenance discharge is likely. The plant should audit its copper-containing equipment and segregate metal-finishing streams before they reach the equalization tank.

Second, the plant must optimize its chemical precipitation pH. Raising the coagulation pH to the 8.5–9.5 range could improve the removal of cadmium [20]. However, because copper is amphoteric, raising the pH excessively may cause copper to re-dissolve. Jar tests must be conducted to find the precise pH setpoint that minimizes the solubility of both metals simultaneously. Any elevation of coagulation pH above the ECR 2023 discharge range (6.5–8.5) would require subsequent re-neutralization of the final effluent before discharge to ensure regulatory compliance.

Third, advanced polishing is required for copper and cadmium. If precipitation fails, ion exchange or adsorption is necessary. Thiophene-functionalized hydrogels have shown exceptional selectivity for heavy metals [30], and low-cost adsorbents and ion-exchange resins have been widely investigated for copper and cadmium removal [29], although site-specific testing would be required to confirm performance under this facility's matrix

conditions. Biochar derived from agricultural waste has been investigated as a low-cost adsorbent for organic pollutants such as dyes [22, 23]; however, its efficacy for heavy-metal removal from complex industrial matrices requires further validation.

Fourth, the iron carryover must be resolved. Adjusting the polymer dosage and increasing the clarifier settling time will prevent coagulant from escaping into the final effluent.

4.5 Environmental, Public Health, and Sustainability Implications

The lead concentrations observed in June (0.191 mg L^{-1}) and July (0.114 mg L^{-1}) have direct ecological consequences. When discharged into the Padma River, lead does not remain in the water column. It rapidly adsorbs onto suspended solids and settles into the riverbed sediments. Once in the sediment, it enters the benthic food web and bioaccumulates in aquatic organisms [7,10]. This poses a direct risk to local fisheries and the communities that consume them.

Furthermore, the use of this water for agricultural irrigation introduces lead into the soil. Unlike organic pollutants, lead does not degrade. It accumulates over time, altering soil microbial communities and reducing crop yields [18]. A recent World Bank assessment identified lead as a top-three environmental pollutant causing premature mortality in Bangladesh [34].

The transition to compliance in November (0.015 mg L^{-1}) demonstrates that the plant is capable of removing lead effectively. However, the episodic exceedances in June and July indicate that operational failures or influent shocks can rapidly reintroduce toxic loads into the ecosystem. This highlights the necessity of continuous, real-time monitoring for heavy metals, rather than relying on infrequent grab samples.

The findings of this study also have direct implications for international sustainability targets. By identifying the failure of conventional treatment to prevent heavy metal toxicity, this work supports SDG 6 (Clean Water and Sanitation), specifically Target 6.3 on reducing hazardous chemical releases. Furthermore, the documented exceedances of neurotoxic lead and carcinogenic cadmium in effluents discharged to the Padma River highlight a direct threat to SDG 3 (Good Health and Well-being) and SDG 14 (Life Below Water). Addressing these issues through source isolation and advanced polishing aligns with SDG 12 (Responsible Consumption and Production) by promoting environmentally sound chemical management in the battery manufacturing sector.

4.6 Integration of Environmental Processes and Pollutant Impacts

This study demonstrates the necessity of evaluating industrial effluents through an integrated environmental framework that spans chemical, physical, and biological processes [12]. The treatment plant relies on physical processes, such as sedimentation and coagulation, alongside chemical processes like pH neutralization, to reduce total dissolved solids and stabilize the effluent. However, the failure to remove copper and cadmium indicates that these physical-chemical mechanisms are insufficient for complete metal partitioning and removal [20, 21]. From a biological perspective, the successful recovery of dissolved oxygen (2.58 to 5.87 mg L^{-1}) supports the biological oxidation of organic matter. However, the persistent discharge of heavy metals poses a direct threat to downstream flora and fauna [26]. As previously discussed, dissolved copper is highly toxic to aquatic flora (inhibiting algal photosynthesis)

and fauna (impairing fish olfaction). Furthermore, lead and cadmium accumulate in riverbed sediments, entering the benthic food web and threatening aquatic ecosystems [7, 10]. Beyond the aquatic environment, the discharge of this effluent into the Padma River directly impacts agricultural soil, where lead accumulation threatens crop yields and soil microbial health [18, 36].

Methodologically, this research highlights the limitations of standard effluent grab sampling for accurate risk assessment [13]. By employing paired influent-effluent sampling, this study provides a more rigorous methodological approach to the study of environmental pollutants. It reveals that relying solely on terminal effluent compliance masks the true toxicity of industrial discharges [15]. Moving forward, environmental monitoring frameworks must integrate paired sampling techniques with expanded heavy metal analyses—including unregulated elements like antimony—to accurately assess the cumulative impacts of industrial pollutants on water, soil, and biological ecosystems [28].

4.7 Circular Economy and Sustainability Implications

The transition from a linear "treat-and-discharge" model to a sustainable, circular approach is essential for the long-term viability of the battery manufacturing sector. The findings of this study offer three pathways toward sustainability.

First, pollution prevention at the source is more sustainable than end-of-pipe treatment. The severe copper exceedance (+107%) suggests that valuable raw materials are being lost to the effluent. Auditing and isolating copper-containing streams (as recommended in Section 4.4) not only prevents aquatic toxicity but also allows for the potential recovery and recycling of copper back into the manufacturing process.

Second, optimizing existing chemical processes is a low-energy, sustainable intervention. Adjusting the coagulation pH to precipitate cadmium and lead more effectively requires no additional capital expenditure or energy consumption. This represents a highly efficient use of existing resources.

Third, the protection of agricultural soil and water resources is a cornerstone of sustainable development. By preventing the discharge of neurotoxic lead and carcinogenic cadmium into the Padma River, this research directly supports the long-term sustainability of local fisheries and agricultural lands that communities depend on for food security and livelihoods. Aligning industrial operations with these sustainability targets is not just an environmental imperative, but an economic one.

4.8 Limitations and Unresolved Questions

This study has critical limitations that constrain the interpretation of the findings. The absence of paired influent metal data prevents the calculation of true metal removal efficiency. We know the plant discharges compliant lead in November, but we cannot determine if it removed 10% or 90% of the influent lead.

Additionally, chromium speciation was not performed. Total chromium was measured, leaving the proportion of carcinogenic Cr(VI) unknown. Finally, the dataset represents a single facility over three sampling campaigns. Seasonal variability and long-term operational trends remain unassessed.

5. CONCLUSION

This study combined effluent-only sampling from June and July 2025 with paired influent-effluent sampling from November 2025. It assessed treatment performance at a lead-acid battery facility in the Ishwardi EPZ. The findings expose a critical dichotomy between conventional compliance and heavy metal toxicity.

The November paired data demonstrated effective treatment of conventional parameters. Mean pH decreased from 9.68 to 7.97, and mean DO increased from 2.58 to 5.87 mg L^{-1}. While TDS removal averaged 22.8%, a critical analysis reveals that November compliance was driven by lower influent loading rather than advanced treatment efficacy.

In contrast, heavy metal compliance was deeply flawed. While lead and zinc complied, copper (2.075 mg L^{-1}), cadmium (0.14 mg L^{-1}), and iron (2.3 mg L^{-1}) exceeded limits by 107%, 40%, and 15%, respectively. Furthermore, antimony was detected at 0.0746 mg L^{-1} but remains unregulated by ECR 2023.

Because influent metals were not measured, true metal removal efficiency could not be calculated. This analytical gap is a critical flaw in the current monitoring framework. Future assessments must mandate paired influent-effluent metal sampling. This will allow true treatment performance to be quantified. It will also enable targeted interventions, such as source isolation for copper, pH optimization for cadmium, and settling adjustments for iron. Without these interventions, the facility will continue to pose a toxic risk to the Padma River ecosystem, despite achieving conventional regulatory compliance.

The transition from intermittent compliance to long-term sustainable industrial practices requires moving beyond basic pass/fail metrics. By implementing paired metal sampling and targeted engineering interventions, regulatory bodies can ensure that industrial activities align with global SDG 6 (Clean Water) and SDG 3 (Good Health) targets. This approach is essential to protect both the ecological integrity of the Padma River and the health of the communities that depend on it.

DECLARATIONS

Author Contributions: M.S.R.: Conceptualization, supervision, methodology, writing—original draft, review and editing, and manuscript revision. M.A.J.: Data curation, formal analysis, and visualization. **Mst. S. R.:** Data curation, formal analysis, statistical computing and verification (R), visualization, and writing—review and editing. M.M.: Data curation, formal analysis, and visualization. S.A.: Investigation, sample collection, quality assurance, laboratory analysis, and writing—review and editing. All authors reviewed, approved, and agreed to the published version of the manuscript.

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