Original Research

Evaluation of Industrial Effluent Treatment Performance and Regulatory Compliance: Implications for Surface and Groundwater Quality in Agro and Leather-Based Industries

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Abstract
The present study investigates the treatment efficiency and regulatory compliance of effluents generated by the sugar factory and distillery and leather-based industries, with implications for surface and groundwater quality. Significant variation in physicochemical characteristics and treatment performance was observed industries. In the sugar factory effluent, notable reductions were achieved with BOD decreasing from 1100 to 70 mg/L (93.6%), COD from 2100 to 320 mg/L (84.8%), and TDS from 5000 to 180 mg/L (96.4%), while TSS removal remained limited at 20%. The distillery effluent treated through a Continuous Processing Unit (CPU) exhibited high efficiency, with COD and TDS reduced from 2500 to 90 mg/L (96.4%) and pH adjusted from 3.3 to 7.5, indicating effective neutralization and pollutant removal. In contrast, leather industry effluent showed poor compliance with discharge standards, as outlet values of TDS (9450 mg/L), COD (2763 mg/L), hardness (1080 mg/L), and alkalinity (1365 mg/L) exceeded permissible limits, reflecting inadequate treatment performance. Heavy metal evaluation suggested elevated concentrations in the leather industry influent, particularly chromium (0.915 mg/L), lead (0.200 mg/L), cadmium (0.065 mg/L), arsenic (0.250 mg/L), and mercury (0.295 mg/L), with only partial reduction at outlet. Sugar factory effluent showed substantial decline in chromium (0.149 to 0.012 mg/L), copper (0.460 to 0.002 mg/L), and lead (0.066 to 0.005 mg/L), whereas distillery effluent exhibited an unexpected increase in chromium (0.046 to 0.283 mg/L). Overall, while progress has been made in improving wastewater management within the sugar and distillery sectors, the leather industry continues to exert considerable pressure on regional water resources.

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Statement of Sustainability: The findings emphasize the importance of continuous monitoring, strict regulatory enforcement, and adoption of cleaner technologies such as zero-liquid discharge (ZLD) systems to ensure long-term environmental sustainability. This research directly contributes to the achievement of United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) by improving water quality and reducing pollution, SDG 12 (Responsible Consumption and Production) through efficient resource and waste management, and SDG 13 (Climate Action) by promoting environmentally responsible industrial practices.

1. Introduction

Freshwater resources are increasingly responsible for water quality deterioration due to rapid industrialization, expanding urban settlements, and intensified agro-industrial activities (Sarker *et al.*, 2021). In many developing areas, surface water bodies and shallow aquifers serve as primary sources of drinking water, irrigation supply, and industrial use (Priyan, 2021). The untreated discharge or inadequately treated industrial effluents into these systems significantly alters their physico-chemical characteristics, leading to elevated biochemical oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), nutrients, and toxic heavy metals. Such alterations not only disrupt aquatic ecosystems but also compromise groundwater quality through infiltration, leaching, and hydraulic connectivity between surface and subsurface systems (Igbinosa and Okoh, 2009). Environmental monitoring frameworks emphasise the need for regular assessment of pollutant sources, treatment performance, and receiving water quality. Within this context, evaluating industrial effluent treatment efficiency becomes critical for understanding the extent to which regulatory standards are met and whether current mitigation strategies are sufficient to protect water resources (Magat and Viscusi, 1990).

Continuous monitoring of effluent parameters and downstream water quality indicators provides evidence-based insights for environmental management and policy enforcement (Rahaman, 2025). Among high water-consuming industries, sugar factories, molasses and grain-based distilleries, and tanneries represent significant point sources of wastewater generation. Although these sectors differ in raw materials and processing technologies, they share a common characteristic: the generation of high-strength effluents with substantial organic and inorganic pollutant waste water (Zhang *et al.*, 2024). Sugar industry effluents are predominantly biodegradable but may cause oxygen depletion in receiving waters if not adequately treated (Kushwaha, 2015). Distillery spent wash is characterized by extremely high organic load and dark coloration, historically contributing to severe water pollution before the adoption of advanced treatment systems (Pant and Adholeya, 2007). Tanneries, in contrast, generate complex effluents containing chromium, sulfides, chlorides, and recalcitrant organic compounds, many of which are toxic and persistent in the environment (Tadesse *et al.*, 2017).

Over the past decade, regulatory authorities, mainly CPCB (Central Pollution Control Board), have introduced stricter discharge norms and promoted advanced treatment approaches such as Zero Liquid Discharge (ZLD), bio-methanation, tertiary polishing units, and Common Effluent Treatment Plants (CETPs) (Bhattacharya and Roy, 2022). While distilleries have increasingly adopted ZLD systems and sugar factories commonly operate Effluent Treatment Plants (ETPs), the performance and operational reliability of these systems vary considerably (Awasare *et al.*, 2015). In many industrial clusters, leather industry wastewater treatment remains inefficient, resulting in recurring exceedance of permissible limits and progressive deterioration of both surface water and groundwater quality. Despite numerous site-specific evaluations, a comparative analysis of treatment efficiency across these industrial sectors and its implications for integrated surface–groundwater monitoring remains limited.

A regular assessment is essential to identify sector-specific strengths and deficiencies, understand cumulative impacts, and guide improvements in environmental monitoring protocols (Ndubuisi and FNisafety, 2025). Therefore, the present study aims to evaluate the efficiency of effluent treatment systems in sugar factories, distilleries, and tanneries and to examine their implications for surface and groundwater quality. The assessment integrates effluent characteristics, treatment performance, regulatory compliance, and environmental risk considerations to suggest informed decision-making and sustainable water resource management.

2. Materials and methods

2.1 Study area

The study was conducted at three major industrial sites in Uttar Pradesh, India. The sugar factory, Balrampur Chini Mills Limited, is located in Balrampur district (27.43° N, 82.18° E; ~105 m amsl). The distillery unit, Rana Sugars Limited, is situated at Bilari in Moradabad district (28.62° N, 78.80° E; ~190 m amsl). The leather Industry (tannery) is located in the Banthar Industrial Area of Unnao district (26.55° N, 80.48° E; ~123 m amsl).

2.2 Study design and sampling strategy

A comparative assessment approach was used to evaluate the efficiency of effluent treatment systems in sugar factories, distilleries, and tanneries. Wastewater samples were collected from representative units of each industry. Sampling points were selected at two critical locations: (i) raw influent entering the treatment system inlet and (ii) treated effluent at the final discharge outlet. Water samples were collected in glass bottles. For heavy metal analysis, samples were preserved immediately with concentrated nitric acid to maintain pH below 2. All samples were transported to the laboratory under refrigerated conditions (4°C) and analyzed within the recommended time.

2.2 Physicochemical analysis of wastewater

Physicochemical parameters of wastewater from all three industries were determined using standard analytical procedures in accordance with APHA guidelines. The parameters such as pH, were evaluated with a digital pH meter, Electron Conductivity (EC) with the help of conductivity meter, for the study of TSS gravimetric method was done, Biological Oxygen Demand (BOD) study were done with a five-day incubation method at 20°C, Biochemical Oxygen Demand (COD) were evaluated with reflex titrimetric method study were evaluated.

For leather industry effluent, special emphasis was given to chromium analysis due to its environmental significance. Total chromium and hexavalent chromium were quantified using Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP-OES) after appropriate digestion procedures.

2.3 Evaluation of treatment efficiency

Treatment efficiency of each industrial unit was calculated by comparing influent and effluent concentrations using following expression (Eq. 1):

$$Treatment\ Efficiency\ (\%) = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \tag{1}$$

where C_{in} represents influent concentration and C_{out} represents treated effluent concentration of a specific parameter. This approach enabled assessment of removal efficiency for key pollution indicators, including BOD, COD, TDS, and chromium. The performance of distillery Zero Liquid Discharge (ZLD) systems, sugar factory Effluent Treatment Plants (ETPs), and leather industry treatment units was comparatively evaluated.

3. Results and discussion

3.1 Physicochemical parameters of the selected industry with removal efficiency

The selected sugar factory demonstrated substantial pollutant reduction through its Effluent Treatment Plant (ETP). BOD removal efficiency level was 93.6%, while COD removal was 84.8%, indicating effective biological oxidation of organic matter. TDS reduction exceeded 96%, reflecting efficient clarification and sedimentation processes showing in (Table 1). However, the outlet COD concentration (320 mg/L) remains moderately elevated, suggesting the need for tertiary polishing to ensure stricter compliance. The distillery effluent shows high organic and dissolved load at the CPU inlet stage. Nevertheless, treatment efficiency exceeded 96% for both COD and TDS, reducing concentrations to 90 mg/L at the outlet, as shown in (Table 2). The neutralization of pH from acidic (3.3) to near-neutral (7.5) further confirms effective treatment performance. These findings indicate that advanced treatment and Zero Liquid Discharge (ZLD)-based systems significantly reduce the pollution potential. In contrast, the leather industry CETP outlet values reveal substantial non-compliance with discharge standards. COD levels were more than ten times higher than the permissible limit, while TDS, hardness, and alkalinity also greatly exceeded regulatory threshold values shown in (Table 3). The elevated salinity and refractory organic load indicate insufficient treatment efficiency and pose serious risks to both surface water and groundwater systems.

Overall, the comparative results show that the distillery treatment system achieved the highest pollutant removal efficiency, followed by the sugar factory ETP. The leather industry CETP exhibited the poorest compliance, indicating that it remains the primary contributor to water quality deterioration among the three industrial sectors evaluated.

The present study demonstrates clear differences in effluent characteristics and treatment performance among the sugar factory, distillery, and leather industry. The findings underscore the importance of treatment technology selection, operational control, and regulatory enforcement in determining final discharge quality and environmental impact. The sugar factory effluent exhibited moderate initial organic loading (COD 2100 mg/L; BOD 1100 mg/L), which was substantially reduced after treatment. BOD removal efficiency (93.6%) indicates effective biological degradation of biodegradable organic matter, suggesting satisfactory functioning of the secondary treatment process. However, COD removal (84.8%) was comparatively lower, and the outlet COD concentration (320 mg/L) slightly exceeded the recommended discharge threshold (250 mg/L). These results suggest the presence of non-biodegradable or slowly degradable organic fractions that are not fully removed by conventional biological treatment alone. In contrast, the distillery effluent demonstrated extremely high pollution potential at the inlet stage. Despite this, treatment efficiency exceeded 96% for both COD and TDS, reducing COD concentration to 90 mg/L at the CPU outlet. The strong reduction factor observed in the log-scale analysis confirms the effectiveness of the Zero Liquid Discharge (ZLD)-based system. Neutralization of pH from acidic (3.3) to near-neutral (7.5) further reflects efficient process control. These findings support the view that strict regulatory frameworks combined with advanced treatment technologies can successfully mitigate even highly concentrated industrial effluents. TDS reduction was substantial in both sugar and distillery sectors, reflecting effective sedimentation, clarification, and evaporative treatment processes. However, the leather industry effluent presented a markedly different profile. The leather industry outlet TDS concentration (9450 mg/L) was approximately 4.5 times higher than the BIS discharge limit, indicating inadequate removal of dissolved salts introduced during tanning operations. Elevated TDS is particularly concerning due to its long-term impact on soil permeability, crop productivity, and groundwater mineralization (Mohanavelu *et al.*, 2021). The compliance analysis further demonstrated that COD in leather industry effluent exceeded permissible limits by more than elevenfold, representing the most critical parameter of concern (Aryanfar *et al.*, 2025). Hardness and alkalinity also exceeded regulatory standards, suggesting incomplete precipitation and insufficient removal of inorganic constituents (Shang *et al.*, 2025). Persistent discharge of such effluent can alter aquifer chemistry and contribute to cumulative salinization. The comparative graphical analysis clearly establishes a technological hierarchy in treatment performance. The distillery sector, operating under ZLD principles, achieved the highest compliance and lowest residual environmental risk. The sugar factory demonstrated satisfactory but improvable performance, with marginal exceedance of COD limits. In contrast, the leather industry showed systemic inefficiency, with multiple parameters exceeding regulatory thresholds. From an environmental concern, these findings highlight the importance of continuous compliance verification and parameter-specific control strategies. While organic load reduction is achievable through biological systems, dissolved solids and refractory organics require advanced or integrated treatment approaches. Failure to address these parameters may lead to progressive deterioration of both surface water bodies and shallow groundwater systems in industrial clusters.

Table 1. Inlet and outlet parameters of the selected sugar factory effluent with removal efficiency.

Parameter	**Inlet**	**Outlet**	**Removal Efficiency (%)**
pH	4.5	6.5	-
TSS (mg/L)	500	400	20.0
TDS (mg/L)	5,000	180	96.4
COD (mg/L)	2100	320	84.8
BOD (mg/L)	1100	70	93.6

Table 2. The inlet and outlet characteristics of the distillery at CPU stage with removal efficiency.

Parameter	**CPU Inlet**	**CPU Outlet**	**Removal Efficiency (%)**
pH	3.3	7.5	-
TDS (mg/L)	2500	90	96.4
COD (mg/L)	2500	90	96.4

Table 3. Leather industry outlet compared with BIS standards for effluent discharge.

Parameter	**Observed value**	**BIS standard for Effluent Discharge**	**Compliance Status**
Ph	9.15	5.5 – 9.0	Slightly Exceeds
TDS (mg/L)	9450	2100	Non- Compliant
Hardness (mg/L)	1080	600	Non- Compliant
Alkalinity (mg/L)	1365	600	Non- Compliant
COD (mg/L)	2763	250	Non- Compliant

3.2 Evaluation of heavy metals in selected industrial effluent samples

The concentrations of heavy metals such as Fe, Mn, Zn, Cr, Cu, Ni, Pb, Cd, Co, As, and Hg in leather industry effluent, sugar factory, and distillery inlet and outlet both samples were evaluated with the help of ICP-OES and compared with CPCB permissible limits for waste water. The leather industry inlet exhibited elevated chromium concentration (0.915 mg/L), substantially higher than other metals in the same stream. Lead (0.200 mg/L), arsenic (0.250 mg/L), and mercury (0.295 mg/L) were also detected at comparatively higher levels. After treatment, chromium concentration decreased markedly to 0.063 mg/L. Similarly, lead reduced from 0.200 to 0.017 mg/L and nickel from 0.100 to 0.045 mg/L. Iron and copper also showed moderate reduction. When compared with CPCB standards, chromium levels were within the permissible limit (2.0 mg/L). However, lead in the inlet (0.200 mg/L) exceeded the CPCB limit of 0.1 mg/L. Mercury concentrations in both inlet and outlet samples were considerably higher than the prescribed limit of 0.01 mg/L showing in (Table 4 and Figure 1).

The sugar factory inlet contained comparatively higher concentrations of copper (0.460 mg/L), nickel (0.717 mg/L), cadmium (0.257 mg/L), and arsenic (0.520 mg/L). Treatment significantly reduced copper (0.460 to 0.002 mg/L), chromium (0.149 to 0.012 mg/L), and cadmium to near negligible levels. Nickel concentration declined from 0.717 to 0.121 mg/L. Arsenic showed partial reduction but remained elevated (0.415 mg/L) in the outlet. According to CPCB standards, arsenic in the inlet exceeded the permissible limit of 0.2 mg/L. Other metals remained within acceptable discharge limits. Negative mercury values indicate concentrations are very low means below detection limits. The distillery inlet showed moderate concentrations of metals such as chromium (0.046 mg/L), nickel (0.061 mg/L), lead (0.032 mg/L), and arsenic (0.131 mg/L). Unlike the other industries, chromium concentration increased in the outlet (0.283 mg/L) compared to the inlet. Minor increases were also observed for copper and cobalt. Most other metals remained within low concentration ranges. All metals were within CPCB permissible limits, although the rise in chromium concentration at the outlet suggests possible operational or process-related factors affecting removal efficiency.

Table 4. Heavy metal concentration (mg/L) in industrial effluent samples.

Industry	**Fe**	**Mn**	**Zn**	**Cr**	**Cu**	**Ni**	**Pb**	**Cd**	**Co**	**As**	**Hg**
Leather Industry Effluent – Inlet	0.071	0.014	0.017	0.915	0.069	0.100	0.200	0.065	-0.001	0.250	0.295
Leather Industry Effluent – Outlet	0.041	0.009	0.012	0.063	0.039	0.045	0.017	0.026	0.033	0.130	0.237
Sugar Factory – Inlet	0.016	-0.001	-0.015	0.149	0.460	0.717	0.066	0.257	0.162	0.520	-17.950
Sugar Factory – Outlet	0.024	-0.001	-0.018	0.012	0.002	0.121	0.005	-0.034	0.065	0.415	-0.521
Distillery – Inlet	0.042	0.011	0.010	0.046	0.016	0.061	0.032	0.065	0.018	0.131	-0.136
Distillery – Outlet	0.030	0.011	0.008	0.283	0.025	0.067	0.018	0.033	0.037	0.128	-0.886
CPCB standard (mg/L)	3.0	2.0	5.0	2.0	3.0	3.0	.1	2.0	-	0.2	0.01

The comparative assessment reveals distinct heavy metal profiles among the three industrial sectors, reflecting differences in raw materials and operational processes. Leather industry effluent exhibited the highest chromium concentration, which is consistent with the use of chromium salts in leather tanning (Zhang *et al.*, 2016). The considerable reduction in chromium and lead at the outlet indicates effective primary treatment mechanisms, likely involving precipitation and sludge separation. However, the presence of mercury above permissible limits in both inlet and outlet streams raises environmental concerns and suggests the need for improved polishing treatment. In the sugar factory unit, elevated concentrations of copper, nickel, and arsenic in the inlet may be attributed to equipment corrosion, boiler systems, or chemical additives. The treatment system demonstrated strong removal efficiency for copper and cadmium, while arsenic removal was comparatively limited. This indicates that conventional treatment processes may not adequately remove certain trace metals without advanced adsorption or filtration systems. The distillery effluent presented comparatively lower heavy metal concentrations overall, which is expected since distillery wastewater is primarily characterized by high organic load rather than metal contamination.

However, the observed increase in chromium concentration at the outlet suggests possible contamination from internal recycling streams or process equipment. This trend highlights the importance of continuous monitoring and operational optimization. From a regulatory perspective, most heavy metal concentrations complied with CPCB discharge standards, except for lead and mercury in leather industry effluent and arsenic in sugar factory influent. Although compliance was largely achieved at the outlet stage, residual concentrations indicate that long-term discharge without advanced treatment may contribute to gradual accumulation in receiving water bodies. Overall, chromium remains the principal contaminant in leather industry discharge, arsenic is significant in sugar factory effluent, and distillery effluent shows comparatively minor heavy metal burden. The findings emphasize the need for industry-specific treatment strategies and periodic regulatory monitoring to ensure sustainable environmental management.

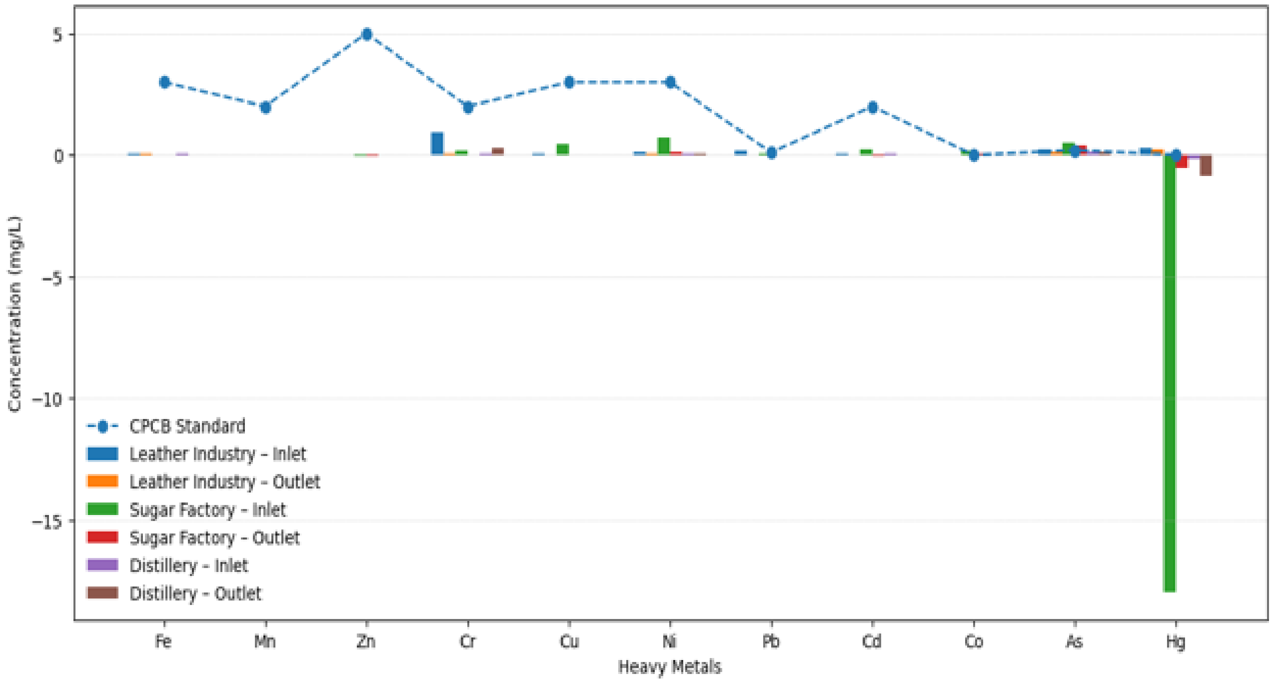

Figure 1. Heavy metal concentration in industrial effluent.

5. Conclusion

The comparative assessment of effluent treatment efficiency among the selected sugar factory, distillery, and leather industry industries reveals substantial differences in pollution control performance and environmental compliance. The distillery (CPU stage) demonstrated the highest removal efficiency (>96% for COD and TDS), confirming the effectiveness of Zero Liquid Discharge-based systems in mitigating high-strength effluents. The sugar factory Effluent Treatment Plant achieved significant reduction of organic load (BOD removal 93.6%), although residual COD levels indicate the need for tertiary treatment enhancement to ensure strict compliance with discharge standards. In contrast, the leather industry Common Effluent Treatment Plant exhibited severe non-compliance, with COD, TDS, hardness, and alkalinity values exceeding permissible limits. The elevated dissolved solids and refractory organic load highlight inadequate treatment performance and suggest that the leather industry sector remains a major contributor to surface and groundwater quality deterioration. Overall, the findings emphasize that technological upgradation, stringent regulatory enforcement, and parameter-specific monitoring are essential to protect water resources in industrial regions. Adoption of advanced treatment systems, particularly for high-salinity and high-COD effluents, is critical for achieving sustainable industrial development and long-term environmental security. The present investigation demonstrates that heavy metal concentrations vary considerably among leather industry, sugar factory, and distillery effluents due to differences in industrial operations and raw material usage. The leather industry effluent was characterized by notably high chromium levels in the inlet stream, confirming chromium as the principal contaminant associated with leather processing. Although substantial reduction in chromium and other metals was achieved after treatment, residual concentrations highlight the necessity for continuous performance evaluation of treatment systems. The sugar factory effluent exhibited elevated concentrations of copper, nickel, and arsenic in the influent, with significant removal efficiency observed for most metals except arsenic, which showed limited reduction. Distillery effluent generally contained lower heavy metal concentrations; however, the increase in chromium at the outlet suggests potential operational limitations or secondary contamination during treatment. Overall, while most treated effluents complied with CPCB discharge standards, isolated exceedances emphasize the importance of regular monitoring and the integration of advanced polishing technologies to ensure long-term environmental protection and sustainable industrial wastewater management.

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Author Contributions

Dr. Shikha Singh: Conceptualisation, methodology, planning, data collection, data interpretation, rough draft of manuscript; Ms. Nalini Dwivedi: Data collection, formal analysis, review and editing; Prof. Seema Paroha: supervision; Prof. Varsha Gupta: supervision, review and editing.

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Conflicts of Interest

The authors declare that there is no financial or personal conflict of interest.

Institutional/Ethical Approval

Not applicable.

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