COST-EFFICIENT TREATMENT OF ACIDIC SPENT ELECTROLYTE USING ALKALINE NEUTRALIZATION AND PRESSURE FILTRATION IN PRECIOUS-METAL REFINING

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Abstract

This study aims to evaluate the technical performance and cost efficiency of an integrated alkaline neutralization and pressure filtration system for eliminating hazardous liquid waste generated from acidic spent electrolyte in a precious-metal refining facility operating under a zero-liquid-discharge configuration. A field-scale quasi-experimental study was conducted at PT X, Indonesia, using NaOH conditioning followed by constant-pressure filtration at approximately 7000 psi. The objective was to determine the optimum operating conditions capable of transforming hazardous liquid waste into a stable solid residue while minimizing waste volume and handling costs. Results show that a NaOH dosage of 100 kg per batch produced a dense, filterable sludge, and that a filtration time of 60 minutes yielded the best dewatering performance. The initial sludge moisture content exceeded 20%, while the optimized process reduced the final moisture content to 14.36%, forming a compact and mechanically stable cake suitable for safe handling. On a system level, the treatment converted 730 m^3/year of liquid hazardous waste into only 45.1 m^3/year of dewatered sludge, representing a 94% reduction in off-site waste volume. Laboratory analysis confirmed effective metal immobilization, with sludge containing 23.64% Cu, 463 mg/kg Ag, and 1 mg/kg Au. The findings demonstrate that the NaOH-assisted filter press functions not only as a dewatering unit but as a strategic hazardous waste minimization tool. By eliminating the liquid phase and stabilizing metal-bearing residues, the system improves operational safety, regulatory compliance, and economic performance.

Keywords: *acidic spent electrolyte, pressure filtration, hazardous waste minimization; zero liquid discharge; sludge dewatering*

Introduction

Industrial gold and silver refining processes produce highly acidic spent electrolyte with a pH range of 1–3 and high concentrations of dissolved base metals such as Cu, Ni, and Zn, as well as residual chlorides and oxidizing agents (Norgate & Haque, 2012; Manyuchi et al., 2022). Due to its highly acidic nature and complex chemical composition, this waste stream poses substantial operational challenges, particularly for efficient metal precipitation, solid-liquid separation, and practical volume reduction in an industrial setting. Traditional wastewater treatment methods, which are generally designed for effluent polishing before discharge, may not be applicable to such waste streams due to their sensitivity to high metal loads, variable chemical composition, and low pH.

From a process engineering standpoint, the main difficulty in treating acidic spent electrolyte is not meeting the discharge standards but eliminating the hazardous liquid phase altogether and stabilizing it as a solid in the

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Received: 14 November 2025
Revised: 31 January 2026
Accepted: 4 February 2026
DOI: 10.23969/jcbeem.v10i1.35888

plant, as envisioned in the basic philosophy of zero liquid discharge (ZLD) systems, which focus more on the elimination of the liquid phase and stabilization of the material within the plant boundary (Tong & Elimelech, 2016). In this case, the effectiveness of treatment is more appropriately measured by the reduction of hazardous waste, phase stabilization, and logistics reduction rather than the traditional effluent quality criteria.

Thus, the treatment of acidic spent electrolyte needs an integrated strategy capable of simultaneously neutralizing acidity, precipitating metals, and allowing for mechanical dewatering. Alkaline conditioning with sodium hydroxide (NaOH) is well established as an efficient strategy for destabilizing dissolved metal species and facilitating the formation of metal hydroxide flocs, thus enhancing sludge structure and filterability (Saveyn et al., 2005; Izydorczyk et al., 2021). Nevertheless, chemical neutralization alone is inadequate if the resulting slurry cannot be further dewatered by mechanical means to form a compact and stable residue amenable to safe handling and further management outside the plant.

Pressure filtration with a filter press is a technically viable solution that uses high mechanical pressure to separate liquid from solids, forming a dense sludge with a lower handling volume. Compared to membrane or ion exchange technologies, filter presses are less affected by high suspended solids concentration, high pH, and variable wastewater composition, making them highly suitable for precious metal refining processes in harsh chemical environments (Dobson & Burgess, 2007; Yan et al., 2021; Grohs et al., 2024). In ZLD-orientated systems, dewatering assumes a critical role in minimizing hazardous waste logistics and stabilizing residual solids for further management (Namdeti, 2023).

While pressure filtration has been widely practiced in mineral processing and tailings management, its application at a field scale for treating acidic spent electrolyte in precious metal refining, especially in a closed-cycle, zero-liquid-discharge system, has been inadequately explored. Most studies have been focused on laboratory-scale experiments or discharge-focused treatment systems, with less attention to evaluating the performance of alkaline conditioning in combination with pressure filtration under continuous industrial operation conditions to minimize hazardous waste volume and facilitate internal material handling (Tong & Elimelech, 2016; Junaidi et al., 2025).

This research fills this gap by assessing the technical efficacy and operational viability of a NaOH-assisted filter press system introduced at an industrial precious metal refining plant in Indonesia. The system is designed as a closed-loop process, with no liquid effluent discharged into the environment. Rather, the efficacy of the treatment process is measured by the transformation of hazardous waste phases, sludge dewaterability, volume reduction, and closure of the material loop. By shifting the focus from the traditional polishing of effluent to waste minimization and logistics optimization, this research makes a useful application of circular economy and ZLD concepts in metal refining plants.

Research Methodology

Research Location

This research was conducted at PT X, a precious metal refinery located in Indonesia that produces spent electrolyte as an acidic byproduct (pH 1–3) during electrorefining operations. The study focused on the full purification line and internal waste management system, encompassing spent electrolyte collection, alkaline conditioning, high-pressure filtration, neutralization, and downstream material recovery processes.

A notable feature of the treatment system examined in this study is its closed-cycle design, which ensures that no liquid effluent is discharged into the external environment. All liquid streams generated during processing are fully contained within the facility and subjected to further in-plant treatment. Rather than functioning as a conventional end-of-pipe wastewater treatment unit, the system serves as an integrated solution for hazardous waste minimization and internal material loop closure.

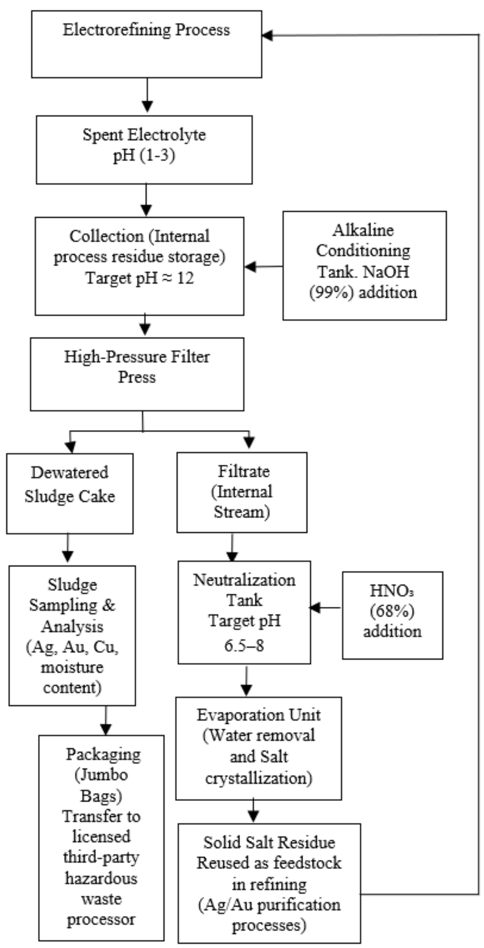

Figure 1. Flow process of spent electrolyte treatment and internal material recovery.

Research Design and System Boundary

This study adopts a field-scale industrial case study approach to evaluate the technical performance and economic feasibility of a closed-cycle treatment system for acidic spent electrolyte generated during precious-metal electrorefining at PT X, Indonesia. The scope of analysis includes the entire internal treatment process, encompassing alkaline conditioning, high-pressure filtration, sludge handling, and downstream material recovery. The system operates in a closed-loop configuration, with no liquid effluent discharged to the external environment. All liquid streams generated during the process are retained within the facility and subjected to further internal treatment. This configuration aligns the system with zero-liquid-discharge (ZLD) principles that prioritise hazardous waste minimisation, material stabilisation, and internal loop closure over compliance with conventional effluent discharge requirements.

Quantitative baseline data on dissolved metal concentrations in the untreated spent electrolyte were unavailable, as the treatment system was introduced primarily as an operational response to hazardous waste-handling constraints rather than as a regulatory-driven wastewater treatment upgrade. Internal monitoring prior to implementation focused primarily on pH control, process consistency, and occupational safety. As a result, detailed analytical records of dissolved metals were not systematically collected or archived.

Given this context, the effectiveness of the treatment system is not evaluated by comparing aqueous metal concentrations before and after treatment. Instead, the study assesses system performance through indicators such as the successful elimination of hazardous liquid waste, the stabilisation and concentration of dissolved metals into a solid phase via alkaline conditioning and pressure filtration, the reduction in hazardous waste volume requiring external handling, and the feasibility of internal reuse of treatment byproducts. The system boundary is explicitly defined within the plant, ensuring that all liquid and solid waste streams remain confined to internal operations. This boundary condition aligns with the study's core objective of achieving closed-loop resource management and waste minimisation, rather than simply ensuring compliance with environmental discharge regulations.

Operational Methodology and Evaluation Framework

The research design incorporates a quasi-experimental methodology conducted under routine operating conditions, using full-scale equipment at the industrial facility. Sodium hydroxide (NaOH, 99%) was applied at varying dosages to evaluate its ability to neutralise the spent electrolyte and generate a stable sludge suitable for pressure filtration. Filtration trials were conducted at a constant operating pressure of approximately 7,000 psi, with treatment durations of 30, 45, and 60 minutes used to assess sludge dewatering efficiency.

The feasibility of alkaline neutralisation was evaluated not solely by the resulting pH value, but by its ability to produce a cohesive and filterable sludge. Conditions were considered successful when the spent electrolyte, after conditioning, formed a stable slurry that could be effectively processed through the filter press without causing clogging or operational failure. In contrast, conditions were classified as unsuccessful when the slurry remained fluid or colloidal, resulting in unstable flocs and poor filtration performance, despite acceptable pH readings. The evaluation approach, therefore integrated pH control, sludge texture, and actual filter press operability, reflecting realistic industrial decision-making criteria.

Each operational condition was repeated during normal plant operations to ensure consistent and reliable observations. System performance was assessed based on the behavior of sludge formation, filtration effectiveness, moisture content of the dewatered residue, and the extent to which the overall volume of hazardous waste was reduced.

To validate treatment outcomes quantitatively, dewatered sludge samples produced under optimal operating conditions were collected and analyzed by an accredited laboratory. The laboratory tests measured the concentrations of silver (Ag), gold (Au), and copper (Cu) using atomic absorption spectroscopy (AAS), along with moisture content determined through gravimetric methods. These analyses served to characterize the solid residues generated by the closed-cycle system and confirm the effective transfer of dissolved metals from the liquid phase into a stable solid matrix. The concentrations of metals in the filtrate were not analyzed, as the liquid fraction remains entirely within the closed-loop system and is not discharged to the external environment. Accordingly, the assessment of treatment performance focused on solid-phase characteristics, the elimination of hazardous liquid waste, and internal waste reduction outcomes, rather than on conventional effluent quality parameters.

Treatment performance is therefore interpreted through internal process outcomes, including sludge filterability, stability of solid residues, elimination of hazardous liquid waste streams, and the potential for reintegration of materials into the refining process.

Primary data for this study were collected on-site and included pre- and post-treatment pH levels, chemical consumption rates for NaOH and acid, filtration time, sludge mass, and total waste volume. Dewatered sludge samples were submitted for laboratory testing to determine their metal content and moisture levels. Secondary data, such as waste handling records, operational logs, and financial data, were obtained from the company's internal documentation system.

The economic analysis was conducted to assess the cost-effectiveness and financial viability of the NaOH-assisted filter press system. This was done by comparing waste management costs before and after the system was implemented. Expenditures were divided into capital expenditure (CAPEX), which covered equipment procurement and installation, and operational expenditure (OPEX), which included chemical use, sludge handling, maintenance, and third-party waste-processing services. This cost classification enables transparent evaluation and facilitates replication of the financial analysis for future industrial applications.

Results and Discussion

Optimisation of NaOH Dosage for Sludge Formation and Dewatering Process

The role of sodium hydroxide (NaOH, 99%) was significant in neutralising the spent electrolyte, which had an initial pH of 1-3, and in facilitating the precipitation of metal hydroxides prior to filtration. The experimental data are presented in Table 1.

Table 1. Experimental pH Neutralisation

Level of NaOH (kg)	Stirring Time (min)	The resulting pH	Spent Electrolyte Texture	Conclusion
25	30	3	fluid	Not feasible
50	30	5	fluid	Not feasible
75	30	7	thick	Not feasible
100	30	12	thick	Feasible

As presented in Table 1, the increment in the NaOH dose caused a corresponding rise in the pH of the spent electrolyte and changes in the physical properties of the slurry. At NaOH doses of 25–50 kg, the mixture was fluid, which meant that the pH was not fully neutralized and the metal hydroxide flocs were not formed properly. This led to the failure of pressure filtration. Even at a higher NaOH dose of 75 kg, the pH was close to neutral (pH ≈ 7), but the slurry was thick, and the floc properties were not stable enough for filter press operation.

Among the NaOH dosages tested in this study, the highest dosage of 100 kg produced the most favourable conditions, raising the pH to around 12 and forming a dense, cohesive sludge that could be filtered using the filter press without operational problems. Therefore, this condition was chosen as the optimum operating condition for further analysis. NaOH dosages above 100 kg were not considered in this study because preliminary results showed that the desired alkaline condition and stable sludge formation had already been attained at this dosage, and further chemical addition was expected to increase operating costs without a corresponding increase in dewatering efficiency.

The high pH condition led to the precipitation of metal hydroxides and the destabilization of colloidal particles, resulting in the formation of dense flocs that could be easily filtered. This is consistent with previous studies reporting enhanced sludge compressibility and water release during pressure dewatering under alkaline conditioning (Saveyn et al., 2005; Izydorczyk et al., 2021). Similar trends have also been observed in gold processing, and mine water treatment plants, where high pH conditions have been reported to improve filtration efficiency (Grohs et al., 2024; Matebese et al., 2024).

Optimum Filtration Time in the Filter Press Process

Pressure-driven filtration was conducted for 30, 45, and 60 minutes at approximately 7000 psi. The effect of filtration on sludge characteristics is summarised in Table 2 and Figure 1

Table 2. Results of Optimum Filtration Time in the Filter Press Process

Time (min)	Moisture Content in Sludge	Sludge Thickness
30	High	Thin and watery
45	Moderate	Thick with small volume
60	Low	Thick

As shown in Table 2 and Figure 1, the sludge's physical characteristics improved progressively with increasing filtration duration. At 30 minutes, the sludge remained thin and watery, indicating incomplete dewatering and high residual moisture content. Extending the filtration time to 45 minutes resulted in a thicker and more cohesive sludge; however, a sticky texture persisted, suggesting that a portion of bound water remained trapped within the floc matrix.

30 minutes of filtration	45 minutes of filtration	60 minutes of filtration

Figure 1. Comparison of the sludge produced at 30, 45, and 60 minutes of filtration

Among the filtration durations evaluated in this study, the longest, 60 minutes, produced the most favorable sludge characteristics, characterized by a dense, compact texture and visibly lower moisture content. Under this condition, the sludge cake exhibited sufficient structural integrity for stable handling and packaging, indicating effective consolidation under constant pressure. Accordingly, a filtration time of 60 minutes was selected as the optimum operating condition within the tested range for subsequent analysis.

Filtration times longer than 60 minutes were not evaluated in this study, as observations during operation indicated diminishing improvements in sludge texture beyond this duration, while longer cycle times were expected to reduce process throughput and increase operational cost. Therefore, the selected filtration time represents a practical balance between dewatering performance and operational efficiency under industrial conditions.

These findings are consistent with previous studies indicating that effective dewatering in constant-pressure filtration depends not only on pressure but also on sufficient residence time to allow water migration through the sludge cake (Saputri et al., 2019; Stickland, 2016). Saveyn et al. (2005) further highlighted that sludge compressibility and floc elasticity govern the release of bound water, explaining why extended filtration within a practical time window—such as the 60-minute interval evaluated in this study—produces a denser and mechanically stable cake. This study evaluated filtration durations up to 60 minutes, the effects of longer filtration times on dewatering efficiency and process economics warrant further investigation

Dewatering Efficiency and Chemical Characterisation of Dewatered Sludge

At the selected operating conditions—100 kg NaOH dosage and 60 minutes of filtration—the filter press system demonstrated measurable dewatering performance under field-scale industrial conditions. The water content of the spent electrolyte was reduced by approximately 6.5%, calculated from the decrease in batch volume from 2.0 m³ to 1.87 m³. Although this reduction is lower than values commonly reported in laboratory-scale studies, it reflects realistic operational performance constrained by factors such as filter cloth condition, sludge compressibility, and the need for continuous plant operation (Stickland, 2016).

From a process engineering perspective, the relatively modest water removal can be attributed to the microstructure of the sludge cake formed during alkaline conditioning. When metal hydroxide flocs exhibit elastic or compressible behavior, a portion of interstitial and bound water becomes trapped within the internal cake structure, limiting further water release even under high pressure (Saveyn et al., 2005). This behavior suggests that improvements in chemical conditioning uniformity, particularly NaOH distribution and mixing intensity, could enhance cake permeability and lead to lower residual moisture levels in future optimization efforts.

To quantitatively validate the outcome of the closed-cycle treatment process, dewatered sludge produced under these operating conditions was analysed by KAN-accredited laboratory. The analytical results are presented in Table 3.

Table 3. Chemical Composition and Moisture Content of Dewatered Sludge

Parameter	Unit	Method	Result
Silver (Ag)	mg/kg	AAS	463
Gold (Au)	mg/kg	AAS	1
Copper (Cu)	%	AAS	23.64
Moisture Content	%	Gravimetric	14.36

The laboratory results indicate that a substantial fraction of dissolved metals present in the acidic spent electrolyte was successfully transferred from the liquid phase into the solid residue through alkaline conditioning and pressure-driven filtration. The dewatered sludge exhibited a high copper concentration (23.64%), along with measurable silver and gold contents, confirming effective metal precipitation and subsequent concentration during the treatment process. Although baseline aqueous metal concentrations were not available, the composition of the sludge provides indirect but compelling evidence that significant quantities of dissolved metals were originally present in the spent electrolyte and were effectively immobilized in the solid phase because of the treatment system.

The measured moisture content of 14.36% further demonstrates that the filter press produced a compact and mechanically stable sludge cake, suitable for safe handling, packaging, and regulated off-site processing. Within the context of a closed-cycle system, these results confirm that treatment performance is achieved primarily through elimination of the hazardous liquid phase and stabilization of metal-bearing solids, rather than through dilution-based wastewater treatment.

Overall, the combined dewatering performance and sludge characterization results demonstrate that, under PT X's specific industrial constraints, the NaOH-assisted filter press system provides a technically viable and operationally practical solution for hazardous waste minimization, while also enabling controlled downstream management of metal-rich residues.

Optimized for the cost-effectiveness and economic viability of the filter press for the application

PT X implemented the filter press system, which led to a large reduction in the operational impact on operational costs that was necessary for hazardous wastewater (spent electrolyte) management. A comparison of volumes that are shown before and after implementation of the filter press process is shown in Table 4.

Table 4. Comparison of volume

Parameter	Before Implementation	After Implementation
Waste Type	Spent Electrolyte (liquid hazardous waste)	Sludge (solid residue after filtration)
Average Daily Volume	2 m³/day	0.123 m³/day
Annual Volume	730 m³/year	45.1 m³/year

**Detailed calculations are explained in the Appendix*

This substantial decrease in volume directly reduced the frequency and cost of third-party disposal, highlighting the filter press not only as a technically viable solution but also a financially strategic investment. Beyond operational savings, this shift represents a broader transformation in waste management practices within the facility—enhancing predictability, stability, and efficiency. These outcomes are consistent with findings by Khan et al. (2025), who emphasize that source reduction and increased resource efficiency are critical to minimizing operational expenditure in circular economy models.

A crucial distinction must be made between two performance metrics: moisture reduction per batch and annual waste volume reduction. The 6.5% moisture reduction refers to the liquid removed during a single filtration cycle—specifically, the reduction from 2.0 m^3 to 1.87 m^3 per batch. This reflects the physical limitation of water extraction from compressible metal hydroxide sludge under constant-pressure filtration.

In contrast, the 94% reduction represents the overall decrease in hazardous waste volume requiring off-site handling over the course of a year. Before the filter press was introduced, the entire stream of spent electrolyte was managed as liquid hazardous waste, totaling approximately 730 m^3/year. After treatment via alkaline conditioning and pressure filtration, the waste requiring external disposal was limited to the dewatered sludge only—45.1 m^3/year.

These two figures reflect fundamentally different aspects of performance. The 6.5% batch-level moisture reduction quantifies dewatering efficiency, while the 94% annual volume reduction captures system-wide improvements achieved through phase transformation from liquid to solid waste. This distinction clarifies that the primary benefit of the filter press lies not in maximizing water removal, but in transforming waste form and optimizing logistics, ultimately reducing environmental risk and disposal costs.

PT X's economic evaluation was performed using standard industrial tariffs and existing contracts. The main cost components are summarized in Table 5.

All cost factors were included under Operational Expenditures (OPEX), covering chemical consumption, transport, sludge handling, and disposal. Capital Expenditures (CAPEX) for filter press installation were excluded as sunk costs, since the focus is on comparative operating efficiency before and after implementation.

Table 5. Cost Components in Economic Evaluation

Cost Component	Unit Cost	Description
Liquid hazardous waste disposal	IDR 2,800,000 / m^3	PPLI standard rates for hazardous liquid waste
Dewatered sludge disposal	IDR 1,750,000 / ton	Cost of processing sludge waste
Sodium hydroxide (NaOH)	IDR 8,000 / kg	Technical reagents from local suppliers
Transport cost	IDR 1,200,000 / trip	Average cost of licensed transportation of hazardous waste

The transformation of waste from liquid to solid resulted in lower unit disposal tariffs (m^3 vs. ton), reduced transport trips, and minimized the burden on hazardous waste processing partners. The 94% reduction in annual waste-handling costs is therefore attributed to this strategic reconfiguration of the disposal pathway—not just water removal, but a full logistical and regulatory transformation of the waste itself.

Regulatory Context and Disposal Pathway

From a regulatory perspective, the use of pressure filtration technology also changes the course of hazardous waste management under Indonesian environmental laws. In line with Government Regulation of the Republic of Indonesia No. 101 of 2014 on Hazardous and Toxic Waste (Limbah B3), the spent electrolyte produced from the refining process is categorized as liquid hazardous waste that demands strict treatment, transportation, and management procedures. After the alkaline conditioning and pressure filtration process, the waste from PT X is changed from liquid hazardous waste to a stabilized solid residue (dewatered sludge). The process reduces environmental risk from leakage and spillage, allowing temporary storage, packaging, and transportation of jumbo bags in accordance with licensed hazardous waste management procedures.

The dewatered sludge is then sent to a licensed third-party hazardous waste processor in line with national regulatory requirements for the storage, transportation, and treatment of solid hazardous waste. This regulatory-compliant process change further emphasizes the importance of the filter press system as a risk mitigation strategy in addition to its cost-saving function in the hazardous waste management system in Indonesia.

Conclusions

This study demonstrates that the integration of alkaline neutralization and pressure filtration is an effective internal hazardous waste minimization strategy under the specific operating conditions of PT X, a precious-metal refining facility generating highly acidic spent electrolyte (pH 1–3) from electrorefining processes. Within the operational range evaluated, a NaOH dosage of 100 kg per batch provided sufficient alkalinity to form a stable sludge structure suitable for mechanical dewatering, while a filtration duration of 60 minutes produced the most favorable sludge characteristics under constant-pressure operation.

Laboratory analysis of the dewatered sludge generated under these conditions confirmed the successful transfer and concentration of dissolved metals into the solid phase. The sludge contained 23.64% Cu, 463 mg/kg Ag, and 1 mg/kg Au, demonstrating effective metal precipitation during alkaline conditioning, followed by concentration via pressure filtration. These results provide quantitative evidence that the treatment system stabilizes metal-bearing residues rather than dispersing contaminants in an aqueous phase.

Under PT X's site-specific constraints, pressure filtration achieved a measured sludge moisture content of 14.36%, enabling the conversion of liquid hazardous waste into a compact and mechanically stable solid residue suitable for safe handling, packaging, and regulated off-site processing. Although the reduction in water content (6.5%) was modest compared with laboratory-scale studies, it reflects realistic field performance limited by equipment configuration, batch capacity, and continuous production requirements.

A key operational outcome of this case study is the substantial reduction in hazardous waste volume requiring off-site handling, from approximately 730 m^3/year of liquid spent electrolyte to 45.1 m^3/year of dewatered sludge. For PT X, this conversion directly translated into annual disposal cost savings of approximately IDR 1.38 billion, underscoring the economic significance of pressure filtration in industrial refining operations, where waste transport and third-party treatment dominate operating costs.

Importantly, the treatment system at PT X operates under a closed-cycle configuration, with no liquid effluent discharged to the environment. Environmental risk mitigation is therefore achieved not through effluent polishing but through elimination of the hazardous liquid phase, stabilization of metal-rich residues, and internal material loop closure. This approach is particularly relevant for refining facilities that handle aggressive wastewater streams and face constraints in conventional discharge-based treatment systems.

Overall, the findings of this case study demonstrate that site-specific process optimization, supported by quantitative sludge characterization and economic analysis, can deliver meaningful technical and financial benefits in hazardous waste management. Future optimization at PT X should focus on improving chemical conditioning uniformity, mixing efficiency, and filter media performance to further enhance dewatering efficiency, while the closed-cycle approach evaluated in this study may be considered for other refining facilities with comparable waste characteristics.

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Appendix 1. Comparison of annual wastewater treatment costs before and after the filter press implementation at PT X

Parameter	Before Implementation	After Implementation	Remarks Calculation
Waste Type	Spent Electrolyte (liquid hazardous waste)	Sludge (solid residue after filtration)	Conversion of liquid to semi-solid waste reduces disposal volume
Average Daily Volume	2 m³/day	0.123 m³/day	Based on plant operation data
Annual Volume	730 m³/year	45.1 m³/year	2 m³ × 365 days
Transport Cost	IDR 2,000,000 per m³	IDR 1,750,000 per m³	Third-party waste handling tariff
Total Annual Cost	IDR 1,460,000,000/year	IDR 78,925,000/year	Direct operating expense for waste management
Cost Reduction (Savings)	-	IDR 1,381,075,000/year	The difference between before and after implementation costs is a 94% reduction.
Filter Press Investment Cost	-	IDR 843,905,706	Equipment, purchases, and installation
Annual Maintenance Cost	-	IDR 486,987,359/year	Includes maintenance, overhaul, and opportunity loss
Total Annual Expenditure	-	IDR 1,330,893,065/year	Investment + annual maintenance
Operating Cost after Implementation	-	IDR 78,925,000/year	Sludge transport
Payback Period	-	1.49 years (excluding depreciation)	Investment ÷ annual savings
Environmental & Economic Benefit	-	Reduced hazardous waste volume, lower disposal cost, supports cleaner production and circular economy principles.	Aligned with cleaner production and zero-liquid-discharge (ZLD) principles (Khan et al., 2025)