

Scenario-Based Life Cycle Assessment of Downstream Hazardous Wastewater Treatment for Environmental Impact Reduction

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Abstract

The rapid growth of industry in Indonesia has led to an increase in Hazardous and Toxic Waste (B3), including liquid waste with complex chemical characteristics that pose high environmental risks. Treatment facilities for B3 wastewater can generate significant impacts such as Global Warming Potential (GWP), Human Toxicity Potential (HTP), and Freshwater Aquatic Ecotoxicity Potential (FAETP). This study evaluates the implementation of treated water recycling using the Life Cycle Assessment (LCA) method with the CML-IA Baseline approach. The functional unit applied was 1 m³ of treated wastewater. Results show that under the baseline scenario, GWP reached 102.89 kg CO₂ eq, HTP 62.92 kg 1,4-DB eq, and FAETP 10.11 kg 1,4-DB eq. Applying recycling scenarios of 30%; 50%; and 80% consistently reduced impacts across all categories. Each 10% increase in recycling volume reduced environmental burdens by approximately 10%. These findings highlight recycling as an effective and measurable strategy to reduce environmental impacts while supporting sustainable production and consumption principles.

Keywords

GWP, Hazardous, HTP, FAETP, Life Cycle Assessment (LCA)

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1. INTRODUCTION

The advancement of technology and the progression of time have accelerated industrialization, leading to significant growth across various industrial sectors in Indonesia. Industrial growth has played a direct role in escalating the quantity of waste produced. This condition is further characterized by the concentration of populations in urban centers and the modernization of multiple facets of daily life as a consequence of urbanization (Edirisinghe et al., 2023; Wikurendra et al., 2024). Such waste primarily originates from production processes, material handling, or the use of chemical substances (Singh et al., 2023; Suprihatin et al., 2023). In accordance with Government Regulation (PP) No. 22 of 2021, this category of waste is classified as Hazardous and Toxic Materials (B3) waste. This classification is based on its intrinsic characteristics, such as: toxicity, corrosivity, flammability, reactivity, and infectious properties as well as its concentration and quantity, all of which may pose potential environmental and health risks, either directly through immediate exposure or indirectly through long-term accumulation and environmental pathway contamination.

Data reported by the Ministry of Environment and

Forestry of the Republic of Indonesia reveal that the volume of hazardous (B3) waste increased by 9.97 tons between 2022 and 2023, indicating an escalating contribution from various industrial sectors to national hazardous waste generation. This B3 waste commonly contains heavy metals which pose significant risks to environmental quality and human health if not properly managed (Pamungkas et al., 2025; Lina, 2021). Significant sources include the chemical processing industry, mining and metallurgical operations, electroplating industries, and various other manufacturing sectors that utilize metal-based technologies (Oladimeji et al., 2024). The physicochemical characteristics of this waste vary depending on the type of industry that produces it. For instance, wastewater from the textile industry commonly contains a mixture of organic and inorganic compounds, including phenolic compounds derived from dyeing processes (Heltina et al., 2024). In contrast, wastewater from the mining sector is typically characterized by elevated levels of total suspended solids (TSS) and heavy metals (Asrifah et al., 2021). More broadly, industrial wastewater often exhibits high concentrations of Biochemical Oxygen Demand (BOD), chemical oxygen demand (COD), nitrogen (N), and phospho-

rus (P) (Yurnalisdell, 2022; Paśmionka et al., 2022). These chemical constituents contribute to adverse environmental impacts, including aquatic toxicity and eutrophication (Pallavi and Kumari, 2024). When discharged into the environment without adequate treatment, such effluents can lead to severe ecological degradation, disrupt environmental equilibrium, and pose significant risks to aquatic and terrestrial life (Suprihatin et al., 2023). These variations influence the required treatment processes (Agoro et al., 2018; Mensah-Akutteh et al., 2022).

Therefore, to preserve environmental quality and ecological balance, all industries that generate waste are required to implement proper waste management practices. This obligation is in accordance with Law of the Republic of Indonesia No. 32 of 2009, Article 20, which stipulates that “every activity and/or business that produces waste must conduct environmental management.” Furthermore, the requirement for waste management aligns with the objectives of the Sustainable Development Goals (SDGs), particularly Goal 12 on “responsible consumption and production.” According to the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia No. 6 of 2021, the management of hazardous and toxic (B3) waste encompasses several key actions, including waste reduction, storage, collection, transportation, utilization, treatment, landfilling, and disposal.

However, not all parties are authorized to carry out waste management activities. According to Government Regulation No. 22 of 2021, the management of hazardous and toxic (B3) waste may only be conducted by companies or institutions that have obtained an official permit from the government. Consequently, industries or companies without such permits are still obligated to ensure responsible waste management by delegating their B3 waste handling to licensed B3 waste management facilities. This delegation of waste management responsibilities results in a transfer of environmental impacts to the B3 waste management facilities. These facilities not only receive the environmental burden originating from other industries but also have the potential to generate additional impacts through their own waste treatment processes. Moreover, B3 waste treatment facilities serve as an integral component of the industrial downstream process and play a strategic role in ensuring comprehensive and sustainable waste management in accordance with the cradle-to-grave principle (Pichtel, 2017). Therefore, comprehensive environmental impact monitoring is essential at this stage.

Liquid waste management practices can contribute to a range of environmental impacts. For instance, global warming potential may increase due to greenhouse gas emissions generated from fuel combustion used to supply energy for treatment operations (Raghuvanshi et al., 2017). Furthermore, eutrophication risks may arise from residual nutrients such as phosphorus, nitrogen, and ammonia present in treated effluents (Patel and Singh, 2022). The release

of heavy metals may also induce toxicity effects on aquatic ecosystems, soils, and human health (Paulu et al., 2021). Collectively, these issues highlight the growing environmental burdens associated with hazardous and toxic waste treatment facilities. The implementation of good housekeeping practices represents an effective strategy for mitigating these environmental impacts, while the adoption of scenario-based management programs is essential to further reduce potential adverse environmental consequences (United Nations Environment Programme, 2011; International Organization for Standardization, 2015). Nevertheless, the effectiveness of such measures necessitates quantitative evidence, which is crucial for facilitating more robust monitoring processes and ensuring comprehensive evaluation of environmental management performance (Organisation for Economic Cooperation and Development, 2017; U.S. Environmental Protection Agency, 2020).

Life Cycle Assessment (LCA) is one of the methodologies that can be utilized to support decision-making in waste management processes (Bisinella et al., 2024). This method is applied to identify the most appropriate programs for reducing environmental impacts by quantifying the potential environmental effects of different management scenarios (Kristanto et al., 2024). The quantified impact potentials such as climate change, human toxicity, resource depletion, and ecosystem damage are subsequently assessed and compared to provide a robust scientific basis for selecting strategies that minimize adverse environmental consequences (Sabet et al., 2023; Anasstasia et al., 2024, 2020), and the scenario with the lowest environmental impact is selected for implementation (Miwornunyuie et al., 2025; Aziz and Nurunnissa, 2022). This approach is consistent with ISO 14040:2016, which states that LCA aims to compile and evaluate the inputs, outputs, and potential environmental impacts of a product system, thereby quantifying both the magnitude of potential impacts and the activities contributing to them. In the Indonesian context, licensed third-party hazardous waste management facilities play a critical and vital role, as they are responsible for managing the majority of hazardous (B3) wastewater generated by various industrial sectors, making their operational performance highly influential on national environmental outcomes. This study was conducted to assess scenarios aimed at reducing environmental impacts in the hazardous wastewater treatment unit of a licensed B3 waste management facility in Indonesia. The environmental impact assessment was carried out using the LCA approach based on the CML-IA Baseline method, with a functional unit defined as 1 m³ of treated wastewater produced.

2. EXPERIMENTAL SECTION

This study was conducted at one of the licensed B3 waste management facilities in Indonesia. The analysis employed a Life Cycle Assessment (LCA) approach with the objective of comparing the potential environmental impacts of several

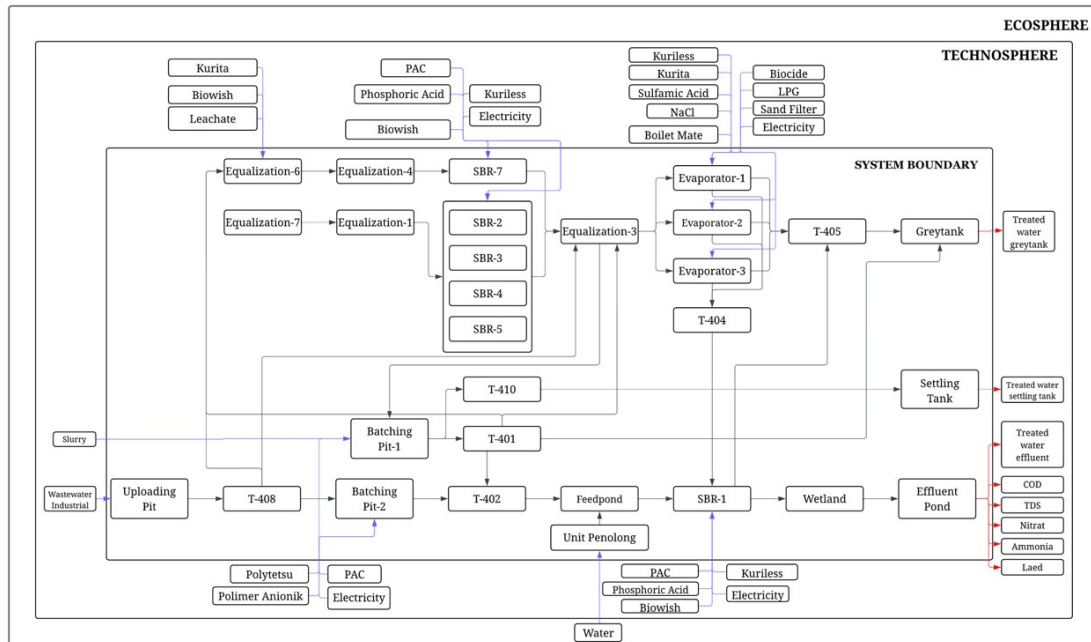


Figure 1. Boundary System of Wastewater Treatment

program scenarios (Figure 1) to minimize hotspots occurring throughout the life cycle of the liquid waste management system. The research was carried out over a one-year period, with the system boundary defined as cradle-to-grave and the functional unit set as 1 m³ of treated wastewater produced from the liquid waste management system.

2.1 Life Cycle Inventory (LCI)

The life cycle inventory for the liquid waste management system utilized a combination of primary and secondary data. Primary data were obtained through direct calculations, field measurements, and laboratory analyses, while secondary data were sourced from the Ecoinvent database and relevant literature. Flow measurements were conducted using flowmeters installed in each treatment unit to determine wastewater discharge, and electricity consumption was measured using voltmeters. Laboratory analyses were performed to determine the material requirements in the treatment process as well as the quality of the treated effluent.

Additionally, emissions estimates resulting from electricity consumption were calculated using the 2006 Intergovernmental Panel on Climate Change (IPCC) Tier-1 guidelines. The emissions is calculated using Equation 1 below, where A is amount of consumption of material type *i* or quantity of product (Wh/kWh/MWh) and EF is emission factor of material type *i* or product *i*.

$$GHG_{emissions} = \sum A_i \times EF_i \tag{1}$$

In addition, pollutions load were calculated using Equa-

tion 2 below base on Appendix II of the Regulation of the State Minister for the Environment No. 1 of 2010, where PL is pollution load; C_w is concentration of wastewater pollutant, Q_w is wastewater discharge, and f is coversion factor.

$$PL = \sum C_w \times Q_w \times f \tag{2}$$

The input data included all requirements involved in the hazardous wastewater treatment process, such as raw materials, auxiliary materials, energy, and natural resources, as presented in Table 1.

- Input Data

The input data encompassed all requirements throughout the liquid waste management process, including main raw materials, auxiliary materials, energy inputs, and natural resources, aggregated over a one-year operational period. The main raw material consisted of industrial waste, represented in the form of a waste flow, while leachate and domestic wastewater were presented as elementary flows. Auxiliary materials obtained from the database included Poly Aluminum Chloride, Phosphoric Acid, NaCl, Sulfamic Acid, LPG, sand, Kurita, Biowish, Kuriless, Biocide, Boiler Mate, Polytetsu, and anionic polymer. The energy input used was electricity, represented as an elementary flow, while the natural resource input consisted of tap water, also obtained from the database.

- Output Data

The output data were derived from primary sources and included the main product, by-products, and emis-

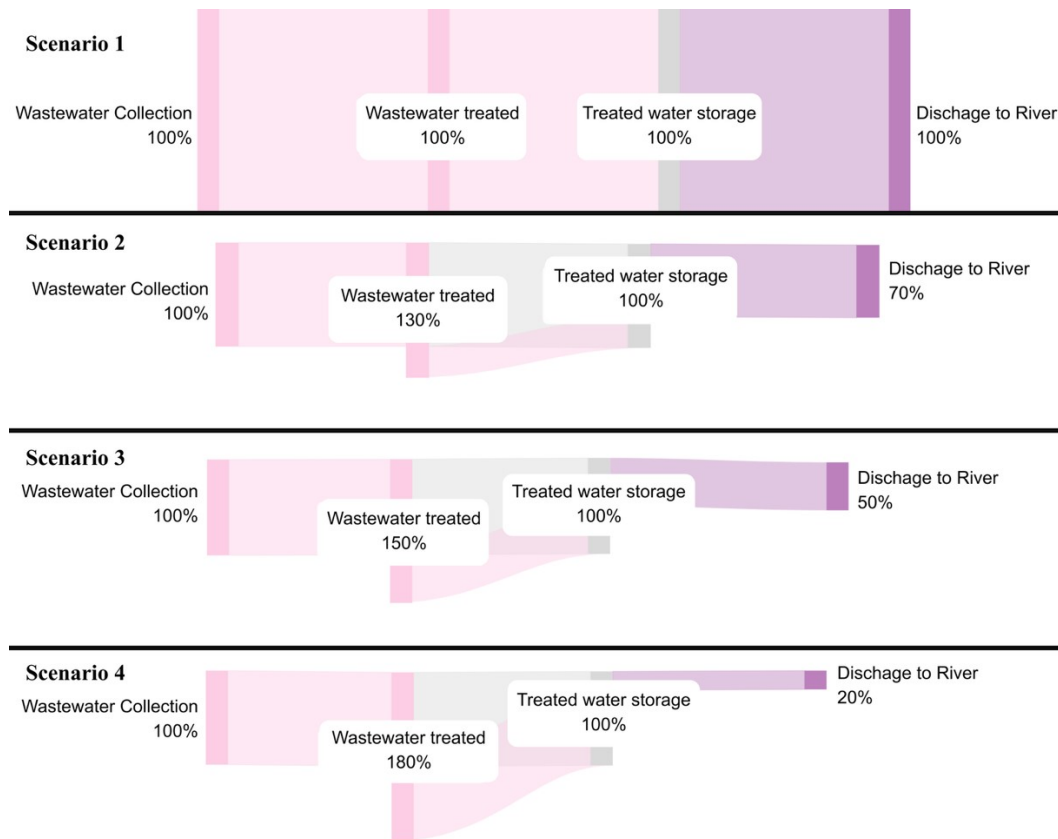


Figure 2. Scenarios Treated Water Recycling Program

sions to air, soil, and water, aggregated over a one-year operational period. The main product generated from the treatment process was treated effluent, while the by-products consisted of process water from the grey tank and settling tank, which were further processed outside the system boundaries defined in this study. The emissions produced included atmospheric emissions in the form of CO₂, soil emissions represented by sludge characterized by the concentration of Mixed Liquor Suspended Solids (MLSS), and water emissions consisting of pollutant loads such as Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS), nitrate, ammonia, and lead.

2.2 Life Cycle Impact Assessment (LCIA)

The collected inventory data were subsequently processed to assess environmental impacts using the OpenLCA software, employing the CML-IA Baseline impact assessment method along with the World 2000 normalization approach. The impact categories analyzed included Marine Human Toxicity Potential (HTP), Freshwater Aquatic Ecotoxicity Potential (FAETP), and Global Warming Potential (GWP). These categories were selected due to their relevance in evaluating the environmental performance of hazardous liquid waste treatment systems.

2.3 Scenario for Wastewater Treatment Plant

The main product, treated effluent, contributed the largest share of environmental impacts compared to the by-products. In this study, an environmental impact assessment was conducted to evaluate the implementation of treated water utilization programs under four different utilization scenarios based on varying percentages of treated water volume: 0%; 30%; 60%; and 90%, as illustrated in Figure 2. Variations in utilization rates influence the material and energy requirements of the system. However, for the purpose of this study, it was assumed that material and energy consumption remained constant across all scenarios. Scenario 1, with 0% utilization, was established as the baseline for comparison.

Monte Carlo simulations with 1,000 iterations were conducted to evaluate the robustness and uncertainty of the Life Cycle Impact Assessment results for three major environmental indicators: Global Warming Potential (GWP100a), Freshwater Aquatic Ecotoxicity (FAETP), and Human Toxicity Potential (HTP). The statistical dispersion, percentile range, and distribution profiles provide insight into the sensitivity of each impact category to variability within the life cycle inventory.

Table 1. Summary of Inventory Data for Wastewater Treatment (FU = 1 m³)

Input			Output		
Name of Flow	Value	Units	Name of Flow	Value	Units
Water	1.26E-01	m ³	Treated wastewater	7.60E-01	m ³
Leachate	1.05E+00	m ³	Treated wastewater in Greentank	2.10E-01	m ³
Industrial wastewater	2.71E-01	m ³	Treated wastewater in Settling tank	2.97E-02	m ³
Domestic wastewater	1.26E-01	m ³	CO ₂	7.26E-02	kg
Kunita	3.54E-02	kg	COD	1.19E+00	kg
Biowish	4.93E-03	kg	Nitrat	6.76E-02	kg
Poly Aluminium	2.62E-01	kg	TDS	2.06E+01	kg
Chloride	5.60E-02	kg	NH ₃	5.28E-02	kg
Phosphoric	5.60E-02	kg	Pb	8.08E-05	kg
Kuriless	2.00E-01	kg	Sludge	1.89E+03	kg
Sulfamic Acid	1.53E-01	kg			
NaCl	1.52E-02	kg			
Biocide	4.27E-05	kg			
Boiler Mate	1.19E-03	kg			
Polytest	8.68E-01	kg			
Polimer Anionik	3.85E-03	kg			
Sand Filter	1.33E-03	kg			
LPG	1.96E-01	kg			
Electricity	6.98E+01	kWh			

3. RESULT AND DISCUSSION

3.1 Inventory Analysis

The inventory data presented in Table 1 indicate that leachate, industrial wastewater, and domestic wastewater serve as the primary raw materials in the treatment process. The leachate originates from the decomposition of waste within the hazardous waste (B3) landfill area located at the B3 waste management facility. Leachate typically exhibits a highly complex and variable composition depending on its age; generally, older leachate contains a higher concentration of hazardous compounds and exhibits lower biodegradability (Aqni et al., 2020). These characteristics influence both the efficiency of the treatment process and the resulting environmental impacts.

The industrial wastewater treated at the facility originates from companies that do not possess independent B3 waste management permits. These industries include sectors such as oil and gas, mining, pulp and paper, textiles, healthcare, hospitality, as well as the chemical, machinery, and metal industries. Meanwhile, domestic wastewater is generated from internal domestic activities within the B3 waste management facility itself. Regarding input inventory data, material usage is dominated by chemical substances, with Poly Aluminum Chloride (PAC) and Kuriless being the most utilized in the Batching Pit, Sequencing Batch Reactor (SBR), and Evaporator units. In the output inventory, sludge and Total Dissolved Solids (TDS) emissions were identified as the dominant contributors to environmental burdens, primarily affecting soil and water systems. Furthermore, atmospheric environmental impacts arise from

CO₂ emissions generated through electricity consumption during the liquid waste treatment process.

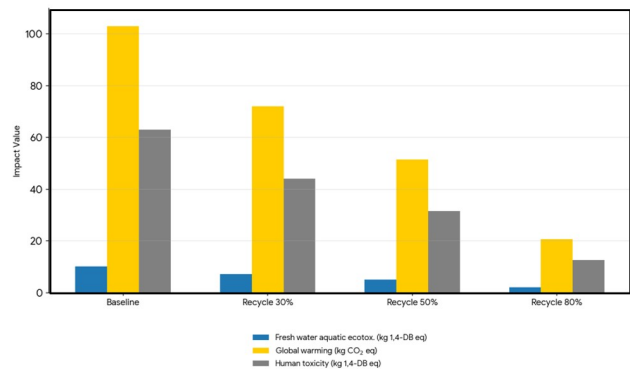


Figure 3. Potential Environmental Impact in Different Recycle Volume Scenarios

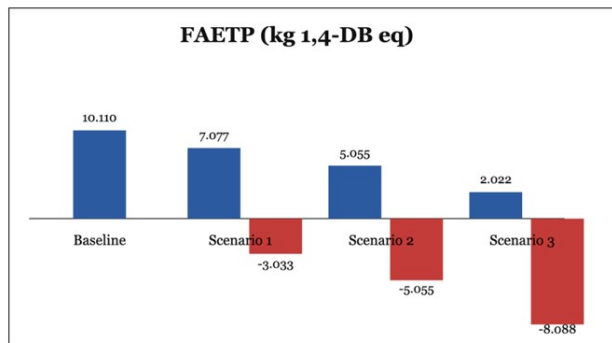
3.2 LCIA at Baseline Scenario

The results of the Life Cycle Impact Assessment (LCIA) for the baseline scenario, based on 1 m³ of treated effluent, are summarized in Table 2. The assessment indicates that the Global Warming Potential (GWP) category reached 102.89 kg CO₂ eq, demonstrating that the liquid waste treatment process generates significant greenhouse gas emissions. These emissions primarily originate from CO₂ released during electricity consumption for industrial operations and chemical production processes within manufacturing sectors, which have been identified as significant contributors

Table 2. Total Impact and Normalization Value of 1 m³ Wastewater Treatment Production

Category Impact	Impact Assessment		Normalization (Pt)
	Value	Units	
Human Toxicity Potential (HTP)	62.92	kg 1,4 DB eq	2.44×10^{-11}
Fresh Water Aquatic Ecotoxicity Potential (FAETP)	10.11	kg 1,4 DB eq	4.28×10^{-12}
Global Warming Potential (GWP)	102.89	kg CO ₂ eq	2.46×10^{-12}

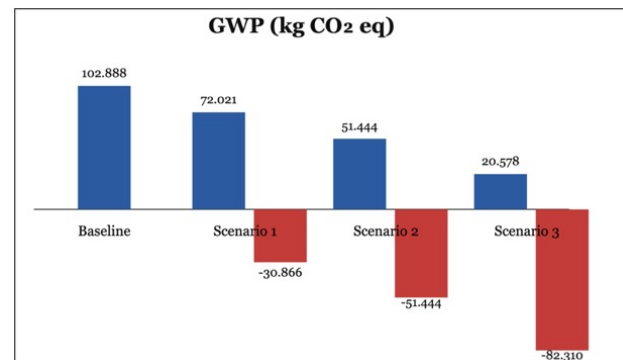
to atmospheric greenhouse gas concentrations and the acceleration of climate change and global warming (Román and Kabir, 2024; Thonemann, 2020). Furthermore, this impact is strongly influenced by the Indonesian electricity mix, which is still predominantly generated from fossil fuels, particularly coal-fired power plants (International Energy Agency, 2022; Kanugrahan et al., 2022).

**Figure 4.** The FAETP Impacts Under Different Recycling Implementation Scenarios

As a result, electricity consumption in the treatment process carries a relatively high carbon intensity, thereby increasing the overall GWP contribution. It is important to note that emissions associated with electricity use are classified as indirect emissions, as they occur during off-site power generation rather than directly within the treatment facility. Meanwhile, the Human Toxicity category exhibited a substantial impact of 62.92 kg 1,4-DB eq, indicating considerable potential risk to human health due to exposure to hazardous substances, including heavy metals, such as lead (Pb). These contaminants can originate from residual sludge, chemical additives, or incomplete removal processes, and may subsequently accumulate in water bodies and sediments, increasing the risk of human exposure through direct contact or the food chain (Hertika and Putra, 2019; Chowdhury et al., 2022). This finding highlights the critical need for controlling chemical residues and emissions in treated effluent, as they can adversely affect human health directly and indirectly.

Furthermore, the Freshwater Aquatic Ecotoxicity (FAETP) category reached 10.11 kg 1,4-DB eq, reflecting meaningful toxicity risks to aquatic ecosystems and signaling the potential for bioaccumulation and biomagnification of

hazardous pollutants within aquatic food chains (Budiastuti et al., 2016). When compared with previous LCA-based hazardous wastewater assessments, important contrasts and alignments emerge. The Vietnam industrial wastewater study reported markedly lower climate change burdens (0.61–0.87 kg CO₂ eq) (Van Tran et al., 2025). Operational optimization and energy efficiency play crucial roles in reducing environmental impacts. Similarly, findings from the textile wastewater Electrocoagulation (EC) LCA study reinforce the dominant influence of electricity consumption and energy dependency on overall environmental burdens. The EC system exhibited significant contributions to global warming (18.13 kg CO₂ eq) and terrestrial ecotoxicity (14.74 kg 1,4-DB eq), with electricity consumption identified as the primary driver of greenhouse gas emissions (Sedaghat et al., 2025). Together, these studies highlight that energy-related factors represent a key determinant of environmental performance in hazardous wastewater treatment systems.

**Figure 5.** The GWP Impacts Under Different Recycling Implementation Scenarios

The baseline LCIA results demonstrate that the existing hazardous wastewater treatment system generates substantial environmental burdens, particularly in terms of GWP, FAETP, and HTP. The notably high GWP value indicates significant dependence on energy-intensive processes and chemical inputs, while the elevated Human Toxicity and FAETP scores highlight potential human health and ecological risks associated with hazardous substance release. Consequently, these results emphasize the strategic importance of controlling toxic emissions as a priority measure to reduce the total environmental burden from B3 waste management facilities. Based on these findings, the imple-

mentation of green housekeeping strategies becomes highly relevant as a preventive measure to minimize toxic emissions. Therefore, targeted interventions such as process optimization, toxic emission control, and the adoption of more energy-efficient or recycling-oriented approaches are essential to reduce the overall environmental footprint of hazardous wastewater treatment systems. One such practice, aligned with waste minimization principles, is the recycling of treated water (Sherman, 2007).

Normalized results as shown in Table 2, indicate that HTP has the highest relative contribution (2.44×10^{-11}), followed by FAETP (4.28×10^{-12}) and GWP (2.46×10^{-12}). This pattern demonstrates that, relative to global environmental burdens, the evaluated wastewater treatment system is most strongly associated with human health risk and aquatic ecosystem toxicity. These findings underscore the need to prioritize strategies that reduce toxic emissions and minimize pollutant release into the environment. In this context, implementing wastewater recycling represents a highly relevant intervention, as it can reduce effluent discharge, lower contaminant exposure risks, and improve resource efficiency. Thus, recycling initiatives are expected to play a key role in decreasing the overall environmental footprint of hazardous wastewater management while supporting more sustainable industrial operations.

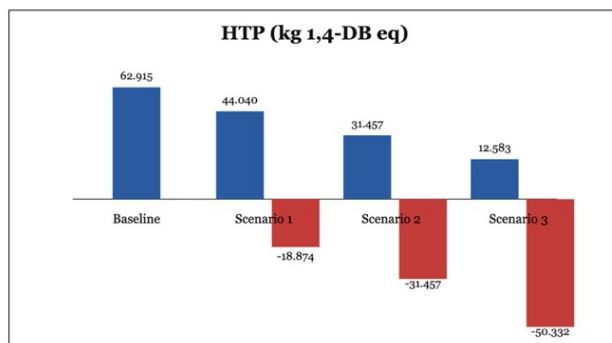


Figure 6. The HTP Impacts Under Different Recycling Implementation Scenarios

3.3 LCIA Result Analysis at Recycle Treated Effluent Scenario

As shown in Figure 3, the implementation of recycling scenarios at 30%; 50%; and 80% consistently reduced environmental impacts across FAETP, GWP, and HTP categories. In the FAETP category, a 30% recycling rate decreased impacts by 3.03 kg 1,4-DB eq, with a further reduction of 2.02 kg 1,4-DB eq observed at 50%. Similarly, GWP decreased by 30.87 kg CO₂ eq at 30% recycling, with an additional 20.58 kg CO₂ eq reduction at 50%. The HTP impacts exhibited comparable trends, with reductions of 18.87 kg 1,4-DB eq and 12.58 kg 1,4-DB eq at 30% and 50% recycling, respectively.

These results indicate a clear, proportional relationship between recycling rate and environmental impact reduction, suggesting that higher recycling volumes directly mitigate emissions and pollutant release. Mechanistically, increased recycling reduces effluent discharge, thereby lowering toxic concentrations in aquatic systems, decreasing energy and resource demand for additional treatment, and minimizing potential human exposure to hazardous substances. Collectively, the findings demonstrate that recycling serves as a quantifiable and scalable strategy for mitigating environmental burdens in industrial liquid waste management. The observed trends provide robust evidence supporting the adoption of higher recycling rates as an effective environmental management intervention.

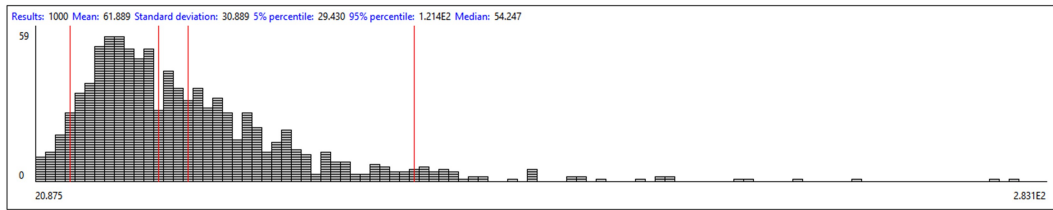
A quantitative sensitivity analysis was conducted to evaluate the response of the system to incremental increases in recycling implementation (30%, 50%, and 80%), as illustrated in Figures 4-6. The calculated variation coefficients demonstrate a consistent and proportional sensitivity across all analyzed impact categories. The results indicate that each 10% increase in recycling volume leads to an average reduction of approximately 10% in overall environmental impacts, confirming a linear and stable system response. This proportionality indicates low uncertainty propagation and high robustness of the model outcomes with respect to changes in recycling intensity.

For HTP (kg 1,4-DB eq), the baseline scenario exhibits the highest impact value (62.92 kg 1,4-DB eq). Under increased recycling scenarios, HTP shows a systematic decline, with Scenario 1 yielding a net reduction driven by a decrease of 18.87 kg 1,4-DB eq, and Scenario 3 demonstrating the strongest sensitivity response, where a negative contribution of 50.33 kg 1,4-DB eq outweighs the remaining positive contribution of 12.58 kg 1,4-DB eq.

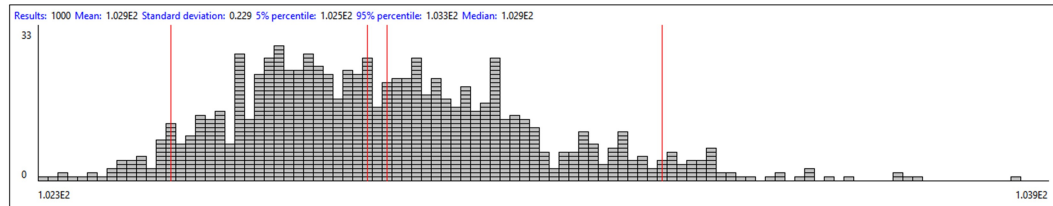
Overall, the quantitative results indicate a reduction magnitude exceeding 80% relative to the baseline under the highest recycling scenario, confirming that HTP is highly sensitive to recycling implementation. In the case of FAETP, the sensitivity analysis reveals a linear reduction trend, with an average decrease of approximately 1.01 kg 1,4-DB eq per 10% increase in recycling capacity. This relationship yields a near-unity sensitivity coefficient, indicating a predictable and directly proportional response of ecotoxicity impacts to recycling intensity. Similarly, greenhouse gas emissions display a strong linear sensitivity, with emissions reduced by approximately 10.300 kg CO₂ eq for every 10% increase in recycling volume. This corresponds to a consistent marginal reduction rate, reflecting the direct influence of recycling on energy demand and emission pathways.

Overall, the quantitative sensitivity analysis confirms that the environmental performance of the system responds linearly and proportionally to recycling intensity across all evaluated impact categories. The magnitude and consistency of the sensitivity coefficients indicate that recycling implementation is a highly effective control parameter, enabling

a) Uncertainty of FAETP



b) Uncertainty of GWP



c) Uncertainty of HTP

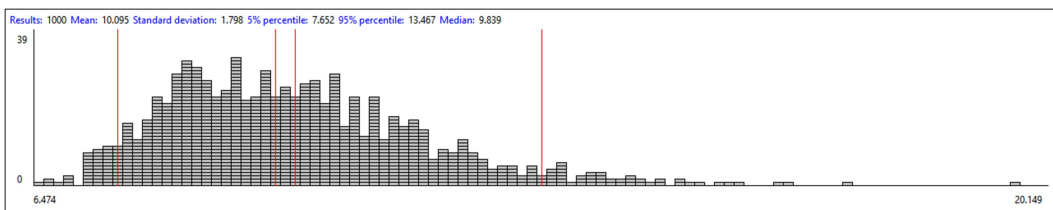


Figure 7. Uncertainty Analysis Results Under Different Recycling Implementation Scenarios

predictable reductions in toxicity, ecotoxicity, and climate-related impacts. These findings reinforce the robustness of recycling strategies as a key mechanism for minimizing environmental burdens and improving resource efficiency within hazardous wastewater management systems.

Figure 7 presents the results of the uncertainty analysis. The GWP exhibits a narrow and symmetrical distribution, with a mean value of approximately 102.900 kg CO₂-eq, a very low standard deviation (0.229), and a restricted 5th–95th percentile interval (102.520–103.320 kg CO₂-eq). These characteristics indicate limited variability and high robustness of the climate-related impact estimates. The tight confidence interval further suggests that uncertainties associated with energy consumption and emission data introduce minimal influence on the overall GWP outcome, thereby supporting the reliability of the estimated climate burden.

In contrast, the FAETP demonstrates a comparatively broader distribution. A mean value of 10.095 kg 1,4-DB eq with a standard deviation of 1.798 results in a substantially wider percentile range (7.650–13.470 kg 1,4-DB eq). These results indicate a moderate degree of uncertainty and sensitivity, implying that ecotoxicity outcomes are more affected by variations in chemical emission inventory data and

associated characterization factors. Nevertheless, the observed variability remains within an analytically acceptable range, and thus the FAETP estimates can still be considered sufficiently reliable for environmental interpretation.

The HTP category presents the highest level of uncertainty among the assessed impact indicators. With a mean value of 61.889 kg 1,4-DB eq, a considerably large standard deviation of 30.889, and an extensive 5th–95th percentile interval (29.430–121.420 kg 1,4-DB eq), the distribution is wide and notably skewed. This reflects strong sensitivity to fluctuations in toxic substance emissions and suggests the presence of poorly constrained or highly variable inventory parameters within the toxicity-related datasets. Accordingly, results in this category should be interpreted with caution, and future assessments would benefit from improved accuracy and representativeness of toxic emission data to enhance overall analytical robustness.

Despite the generally robust outcomes observed for several impact categories, it is important to acknowledge that LCA results are inherently influenced by underlying assumptions, system boundaries, and the quality and representativeness of the life cycle inventory databases used. Limitations related to data availability, reliance on secondary databases for certain emission flows, and the use of generic charac-

terization factors particularly for toxicity-related impacts may introduce uncertainty that cannot be entirely eliminated. Therefore, while the uncertainty analysis demonstrates an acceptable level of confidence for comparative and decision-support purposes, the results should be interpreted as indicative rather than absolute values. Continuous improvement of site-specific inventory data, especially for hazardous substance emissions, is essential to reduce uncertainty and strengthen the reliability of future LCA-based environmental evaluations.

4. CONCLUSIONS

This study employed a Life Cycle Assessment (LCA) approach to evaluate the potential environmental impacts of a B3 waste treatment facility. The assessment of 1 m³ of treated effluent revealed three primary impact categories: Global Warming Potential (GWP) at 102.89 kg CO₂ eq, Human Toxicity Potential (HTP) at 62.92 kg 1,4-DB eq, and Freshwater Aquatic Ecotoxicity Potential (FAETP) at 10.11 kg 1,4-DB eq. Normalization results identified Human Toxicity Potential (HTP) as the largest contributor to the global environmental burden. To mitigate environmental impacts and prioritize the control of greenhouse gas emissions and toxic substance disposal, a treated water recycling program was implemented under three scenarios: 30%; 50%; and 80% of the total treated effluent volume. The results of these scenarios demonstrated consistent and proportional reductions across all impact categories, indicating that the reuse of treated effluent plays a significant role in reducing environmental burdens. Furthermore, sensitivity analysis revealed a stable relationship between environmental impacts and increases in recycling volume, showing that every 10% increase in recycled water corresponds to approximately a 10% reduction in environmental impacts. These findings reinforce the strategic potential of implementing treated water recycling as an effective and measurable environmental mitigation strategy.

5. ACKNOWLEDGEMENT

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