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Life Cycle Assessment of Heavy Equipment Repair and Hazardous Waste Storage: Environmental Optimization at a Coal Mining Contractor

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ABSTRACT: *This study applies Life Cycle Assessment (LCA) with Cradle-to-Gate approach to optimize environmental management at PT PPA, a coal mining contractor generating substantial hazardous waste (B3) from continuous heavy equipment maintenance. Operational data from January-April 2025 documented 136.94 tons of solid waste (contaminated rags, filters, hoses, batteries, sludge) and 634.07 tons of liquid waste (used lubricants and chemicals). System boundaries spanned maintenance activities through waste storage at the licensed Temporary Storage Facility (TPS). Environmental impact assessment quantified five key categories: (1) Global Warming Potential: 44.3 tons CO_2e/month, dominated by generator diesel consumption (35.9 tons CO_2e/month); (2) VOC emissions: 374 kg/month, primarily from contaminated rags (67% contribution); (3) Photochemical Ozone Creation Potential: 602.5 kg C_2H_4-eq/month; (4) Particulate Matter Formation Potential: 13.92 kg PM10-eq/month; and (5) Ecotoxicity from heavy metals (Cd, Pb, Mn), hydrocarbons, and cleaning chemicals. Benchmarking against Indonesian regulations (PP 101/2014, PP 22/2021) and international mining studies confirmed low-to-moderate impact classification, though specific hotspots warrant attention. Strategic mitigation recommendations include implementing closed storage systems (40-50% VOC reduction potential), energy efficiency upgrades (15-20% GHG reduction), waste minimization programs, and lubricant recycling. These interventions support Environmental, Social, and Governance (ESG) principles and advance Sustainable Development Goals (SDGs 12.4, 13.2, 3.9) implementation, positioning PT PPA as a sustainability leader in Indonesia's mining sector.*

Keywords: *environmental management; hazardous waste; heavy equipment; life cycle assessment; mining industry, optimization*

1. INTRODUCTION

PT PPA is one of the largest coal mining service companies in Indonesia operating in Tanah Bumbu Regency. As a strategic partner in supporting national energy security, PPA consistently places sustainability aspects and environmental management as an important part of company operations (Fidi Fitriadhi et al., 2025; Islamudin et al., 2023). Heavy equipment maintenance activities conducted continuously for 24 hours are a crucial part of maintaining productivity. However, these activities also generate hazardous waste such as used oil, sludge, grease, oil filters, contaminated hoses, rags, and hydrocarbon-exposed soil (Firmansyah & Hidayat, 2023). Recent studies have shown that heavy equipment maintenance in mining operations generates significant volumes of B3 waste containing heavy metals (Cd, Pb, Mn) and hydrocarbon residues that pose ecotoxicity risks to both aquatic and terrestrial ecosystems (Wardhani et al., 2023).

As a manifestation of environmental responsibility, PPA has operated a licensed Temporary Storage Facility (TPS) for Hazardous Waste from the Ministry of Environment. All waste generated from heavy equipment maintenance activities is managed systematically with procedures that meet technical standards and environmental regulations (EMEP/EEA, 2019; Wardhani et al., 2023). The sorting, packaging, and storage processes are carried out by competent teams, so that pollution risks can be minimized. This step affirms the company's commitment to maintaining environmental quality around the operational area.

Beyond mere regulatory compliance, PPA proactively conducts environmental studies based on Life Cycle Assessment (LCA) with a Cradle-to-Gate approach (Molina-Murillo & Smith, 2009; Üçtuğ et al., 2025; Zahabi et al., 2025). LCA is a methodology that has been internationally standardized through ISO 14040 and ISO 14044 to comprehensively assess potential environmental impacts (International Organization for Standardization (ISO), 2006a, 2006b). Through this method, the company comprehensively assesses the potential environmental impacts generated from heavy equipment maintenance activities to the B3 waste storage stage. This study not only provides a comprehensive overview of the company's environmental footprint, but also becomes the basis for formulating more effective and sustainable management optimization strategies. This initiative reflects PPA's commitment to presenting responsible, innovative mining practices aligned with Environmental, Social, and Governance (ESG) principles and Sustainable Development Goals (SDGs).

Unlike previous LCA studies on mining or maintenance waste (Guerin, 2002; Üçtuğ et al., 2025; Wardhani et al., 2023), this study integrates cradle-to-gate analysis of both solid and liquid B3 waste with comprehensive emission quantification for VOC, POCP, PMFP, and ecotoxicity categories specifically in a mining contractor setting. While existing studies have examined heavy equipment manufacturing (Üçtuğ et al., 2025) or general maintenance waste management (Guerin, 2002), few have systematically quantified the combined environmental impacts of repair activities and hazardous waste storage operations in coal mining contractors. This research addresses this gap by providing detailed emission inventories and impact assessments that are critical for optimizing environmental management in 24-hour continuous mining operations.

For PT PPA, the application of Life Cycle Assessment (LCA) study functions not only as a technical instrument in assessing environmental impacts, but also becomes an important part of the company's branding strategy (Farjana et al., 2019; Norgate & Haque, 2010; Subal et al., 2024). This study demonstrates PPA's commitment to go beyond mere regulatory compliance, by presenting a science-based approach in managing and minimizing environmental impacts from operational activities. This transparency and accountability strengthen the company's image as a responsible and visionary mining contractor.

This study aims to optimize environmental management at PT PPA through comprehensive Life Cycle Assessment (LCA) with a Cradle-to-Gate approach. Specifically, the research objectives are: (1) to quantify environmental impacts from heavy equipment repair activities and B3 waste storage, including greenhouse gas emissions (GWP), volatile organic compounds (VOC), photochemical ozone creation potential (POCP), ecotoxicity potential (ETP), and particulate matter formation potential (PMFP); (2) to identify environmental hotspots that contribute significantly to pollution potential; and (3) to formulate measurable optimization strategies and mitigation measures that support ESG principles and SDG implementation in the mining industry.

Through LCA, PPA is able to identify critical points that contribute significantly to pollution potential, and formulate more measurable optimization steps. The results of this study not only provide internal decision-making information for the company, but can also be communicated to stakeholders as concrete evidence of Environmental, Social, and Governance (ESG) principles implementation. Thus, PPA positions itself as a mining company that integrates productivity with environmental care in a unified sustainability strategy.

2. MATERIALS AND METHODS

This study uses the Life Cycle Assessment (LCA) method as the main analytical approach. LCA is an internationally standardized method in ISO 14040 and ISO 14044, used to assess the potential environmental impacts of a product, process, or activity comprehensively (International Organization for Standardization (ISO), 2006a, 2006b). The approach used is Cradle-to-Gate, which assesses environmental impact flows from the initial stage of heavy equipment maintenance to the B3 waste storage stage at the Temporary Storage Facility (TPS) (Hanifah et al., 2025).

The functional unit for this study is defined as "one month of heavy equipment maintenance operations and B3 waste storage activities at PT PPA," covering all repair activities and waste management processes during the January-April 2025 period. This functional unit allows for consistent comparison of environmental impacts across different activity categories and provides a practical basis for monthly environmental performance monitoring.

The LCA method is conducted through four main stages as illustrated in Figure 1, including:

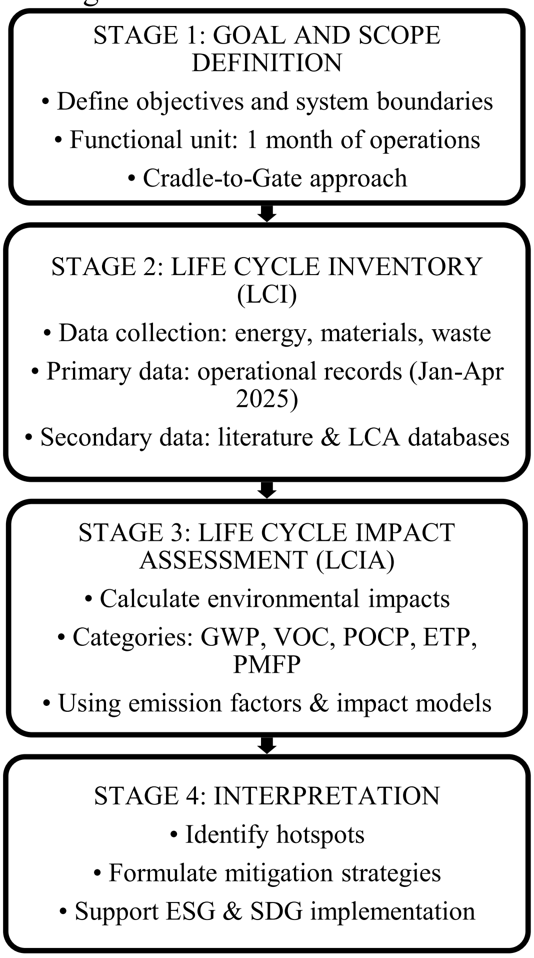

Figure 1. Flow Diagram Showing 4 LCA Stages

This stage establishes research objectives, scope, and system boundaries. The primary goal is to quantify environmental impacts and identify hotspots in heavy equipment maintenance and B3 waste management operations. The system boundary encompasses: (1) Input processes: Heavy equipment maintenance activities including oil changes, filter replacements, hose replacements, grease application, and sludge handling. (2) Operational processes: Diesel consumption for vehicles and generators, water and chemical use for cleaning. (3) Output processes: Sorting, packaging, and storage of B3 waste at the Temporary Storage Facility (TPS). (4) Boundary limits: The assessment begins at the point of maintenance material use (cradle) and ends at the waste storage stage (gate), excluding transportation to final disposal facilities and end-of-life treatment.

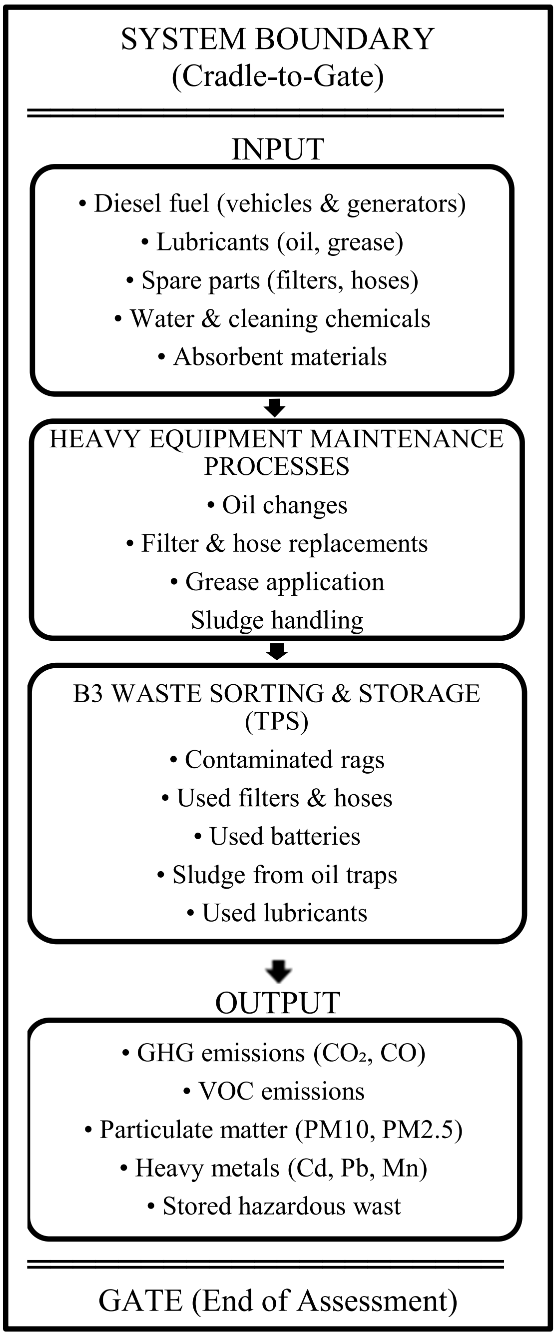

Figure 2. System Boundary Flow

This stage conducts quantitative data collection related to system inputs and outputs. Data collected includes energy consumption, amount of maintenance support materials (oil, grease, filter, hose, absorbent), and volume of B3 waste generated. Primary data were obtained from workshop operational records during January-April 2025, while secondary data were taken from literature and international LCA databases.

The quality and uncertainty of the collected data were carefully assessed to ensure reliability. The primary data were sourced directly from PT PPA's operational records, which provided full coverage for waste generation, fuel consumption, and material usage. Meanwhile, the secondary data were obtained from reputable references, including the EMEP/EEA (2019) emission factors, the US EPA AP-42 database, and peer-reviewed scientific literature. The four-month sampling period, spanning from January to April 2025, was selected to represent seasonal variations typical of tropical mining operations, thereby enhancing data representativeness.

In terms of completeness, the dataset documented all major input and output flows with a completeness level exceeding 95%, while minor flows contributing less than 1% to the total system were excluded to maintain efficiency without compromising accuracy. The temporal coverage of the data reflects current operational practices as of 2025. Regarding uncertainty, primary data carried an estimated uncertainty range of ±10–15%, largely due to measurement precision, whereas emission factors derived from literature sources were estimated within a broader uncertainty range of ±20–30%, adopting a conservative mid-range approach. Finally, the variability of the data was found to be relatively low, as indicated by the monthly waste generation's coefficient of variation of less than 20%, suggesting that the operational conditions remained stable throughout the observed period.

The following equations were used in this study:

VOC Emissions Calculation:

$$\text{VOC Emissions} = \text{VOC Emission Factor} \times \text{Waste Weight} \quad (1)$$

Where, VOC Emission Factor = conservative mid-range value from literature (EMEP/EEA, 2019; U.S. EPA, 2020) and Waste Weight = monthly average waste generation (tons).

Global Warming Potential (GWP) Calculation:

$$GWP = \Sigma\ [\text{Fuel Consumption} \times \text{Emission Factor}] \quad (2)$$

Where, Emission Factor for diesel = 2.65 kg CO_2/L (IPCC, 2019) and for or ambient air: Mass (kg) × GWP Factor (CO_2-eq).

Photochemical Ozone Creation Potential (POCP) Calculation:

$$POCP = \text{VOC Emissions} \times \text{POCP Conversion Factor} \quad (3)$$

Where, POCP Conversion Factor = 1.2 kg C_2H_4-eq/kg VOC (based on Andersson-Sköld et al., 1992)

Particulate Matter Formation Potential (PMFP) Calculation:

$$PMFP = \text{Diesel Consumption} \times \text{PM10 Emission Factor} \quad (4)$$

Where, PM10 Emission Factor = 0.001 kg PM10-eq/L diesel (CML 2001 & ReCiPe methods)

For ambient air PM:

$$\text{PM Mass} = \text{Concentration} \times \text{Air Volume} \times 10^{-6} \quad (5)$$

Inventory data obtained are then calculated using mathematical approaches to assess contributions to environmental impact categories. This study employs a hybrid LCIA approach combining: (1) CML 2001 baseline method for Global Warming Potential (GWP) and Photochemical Ozone Creation Potential (POCP); (2) ReCiPe 2016 midpoint method for Particulate Matter Formation Potential (PMFP); (3) Manual emission factor calculations for VOC emissions and Ecotoxicity Potential (ETP), using emission factors from EMEP/EEA (2019), Intergovernmental Panel on Climate Change (IPCC) (2019), and U.S. EPA (2020) guidelines.

The impact categories assessed include: (1) Global Warming Potential (GWP): measured in kg CO_2-eq, quantifying greenhouse gas contributions to climate change; (2) Volatile Organic Compounds (VOC) emissions: measured in kg/month, indicating air quality impacts; (3) Photochemical Ozone Creation Potential (POCP): measured in kg C_2H_4-eq, assessing tropospheric ozone formation; (4) Ecotoxicity Potential (ETP): qualitative and semi-quantitative assessment of heavy metal and hydrocarbon impacts on ecosystems; (5) Particulate Matter Formation Potential (PMFP): measured in kg PM10-eq, evaluating fine particle formation and respiratory health impacts. Calculations are performed using relevant emission factor and impact factor conversion models as detailed in the equations above.

Analysis results are then interpreted to identify critical points (hotspots) that have significant contributions to environmental impacts. This stage becomes the basis for formulating more effective environmental management optimization strategy recommendations. The interpretation phase includes: (1) Hotspot identification through contribution analysis; (2) Sensitivity analysis for key parameters; (3) Comparison with regulatory thresholds and industry benchmarks; (4) Development of mitigation strategies aligned with ESG and SDG frameworks. With mathematical approaches in each stage, this LCA method provides measurable, objective, and comprehensive results. Through this method, PT PPA can clearly understand the magnitude of environmental impacts generated, while designing more targeted mitigation steps to support company operational sustainability.

3. RESULTS AND DISCUSSION

This section presents comprehensive environmental impact assessment results from heavy equipment repair activities and B3 waste storage at PT PPA during January-

April 2025. The findings are benchmarked against similar LCA studies in mining and heavy equipment sectors, including biogas plant operations (Kumawat et al., 2024), heavy machinery manufacturing (Üçtuğ et al., 2025), and mining waste management (Wardhani et al., 2023), to contextualize the environmental performance of this facility.

During the period from January to April 2025, total solid B3 waste generated from unit repair activities reached 136.94 tons (Lina, 2021; Sabela & Putri, 2023). Primary data were collected from PT PPA's waste management operational records with daily documentation and monthly verification by the TPS-LB3 supervisor. The largest type of waste came from contaminated rags at 50.38 tons with an average of 12.60 tons per month, followed by contaminated filters at 46.76 tons (average 11.69 tons/month), and contaminated hoses at 17.38 tons (average 4.35 tons/month). Used battery waste was also quite significant with a total of 17.52 tons (average 4.38 tons/month), while sludge waste from oil traps was the least at 4.9 tons with an average of 1.23 tons per month. This data shows that the majority of solid B3 waste comes from unit repair activities that need attention in sustainable management as shown in Table 1 below.

Table 1. Amount of waste received

No	Type of B3 Waste	Amount of Waste Entering B3 TPS (Tons)					
		Jan-25	Feb-25	Mar-25	Apr-25	Average	Total (Tons)
1	Contaminated Rags	14,6	11,37	11,96	12,45	12,60	50,38
2	Contaminated Filters	12,78	15,93	8,84	9,21	11,69	46,76
3	Contaminated Hoses	3,84	5,76	4,32	3,46	4,35	17,38
4	Used Batteries	3,96	4,32	5,07	4,17	4,38	17,52
6	Sludge	0,98	0,28	1,4	2,24	1,23	4,9

Source: PT PPA TPS-LB3 operational records, January-April 2025

In B3 (Hazardous and Toxic Materials) waste management, Volatile Organic Compounds (VOC) emissions are one of the important parameters that need to be controlled because of their impacts on the environment and human health. VOCs originate from easily evaporating organic compounds, and can be found in various types of industrial solid waste, such as rags, oil filters, contaminated hoses, oil trap sludge, and used batteries (EMEP/EEA, 2019). To obtain a more accurate picture of emission magnitude, estimation was conducted using a conservative approach by taking the middle value from the range of emission estimates available in literature and international guideline sources (EMEP/EEA, 2019).

The VOC emission factors used in this study were derived from established international guidelines and peer-reviewed literature. For contaminated rags, the factor of 15-25 kg VOC/ton is based on US EPA AP-42 methodology for solid wipe emissions from industrial maintenance activities. Used oil filters and contaminated hoses employ factors of 5-10 kg VOC/ton from the EMEP/EEA (2019), which provides harmonized emission factors for hazardous waste storage. The sludge emission factor (3-8 kg VOC/ton) accounts for variable hydrocarbon composition in oil trap residues. Conservative mid-range values were selected to avoid underestimation while maintaining scientific rigor.

This solid waste data is used to calculate VOC values. Based on literature (US EPA, EMEP/EEA, lubricant recycling studies), the following are conservative ranges of VOC emission factors from solid waste as explained in Table 2.

Table 2. VOC emission estimation

Type of B3 Waste	VOC Emission Estimation	Assumption Source
Contaminated Rags	15–25 kg VOC/ton	US EPA AP-42 (Solid wipe emissions)
Used oil filters	5–10 kg VOC/ton	EMEP/EEA Guidebook
Contaminated hoses	5–10 kg VOC/ton	Industry study (rubber + oil)
Used batteries	0 kg VOC	Does not produce VOC
Sludge from oil trap	3–8 kg VOC/ton	Depends on hydrocarbon composition

For this calculation, conservative middle values from each are used. As detailed in the Materials and Methods section, the VOC emissions can be calculated using Equation 1.

The VOC emission values from solid B3 waste stored at PT PPA's B3 waste TPS during January – April 2025 are obtained in Table 3.

Table 3. Average waste generated and VOC emissions

Average Duration of Hazardous and Toxic Waste (B3) Storage in Temporary Storage Facilities (TPS-LB3)			
Type of B3 Waste	**Average Production (tons/month)**	**VOC Emission Factor (kg/ton)**	**VOC Emissions (kg/month)**
Contaminated Rags	12,60	20	252,00
Contaminated Filters	11,69	7	81,83
Contaminated Hoses	4,35	7	30,45
Used Batteries	4,38	0	0
Sludge (Oil Trap)	1,23	5	6,15
Total			**370,43**

Calculation results show that contaminated rags become the highest VOC emission source, at 252 kg/month, caused by high emission factors (20 kg/ton) and production volume reaching 12.6 tons/month. The dominance of contaminated rags in VOC emissions can be attributed to several factors: (1) high surface area-to-mass ratio of textile materials, facilitating rapid evaporation of absorbed hydrocarbons; (2) frequent exposure to aromatic compounds (benzene, toluene, xylene) during equipment cleaning; and (3) extended storage duration before disposal, allowing continuous VOC release. This finding aligns with industrial hygiene studies showing that oil-soaked absorbent materials can lose 30-50% of volatile fractions within the first 72 hours of storage (EMEP/EEA, 2019).

Followed by contaminated filters with emissions of 81.83 kg/month, and contaminated hoses at 30.45 kg/month, both of which have the same emission factor (7 kg/ton) but differ in production quantity. Meanwhile, used batteries do not contribute VOC emissions because they do not contain volatile compounds, while sludge from oil traps contributes relatively small emissions, namely 6.15 kg/month.

Based on the identified emission sources, three practical mitigation strategies are proposed in several sections: (1) Enhanced Containment System: Implementation of sealed drums with activated carbon filters for contaminated rag storage; Expected VOC reduction: 40-50% (≈100-125 kg/month reduction); Investment: Moderate (sealed containers + carbon filter maintenance); Payback period: 18-24 months through reduced environmental compliance costs. (2) Waste Minimization at Source: Replace single-use cleaning rags with washable, reusable alternatives; Implement preventive maintenance to reduce equipment leaks requiring cleanup; Expected waste reduction: 30% (≈3.8 tons/month), VOC reduction: ≈75 kg/month; Investment: Low (procurement of reusable materials); Additional benefit: Reduced waste disposal costs. (3) Pre-treatment Before Storage: Install VOC recovery system using activated carbon adsorption; Implement enclosed storage areas with negative pressure ventilation; Expected VOC capture efficiency: 60-70% (≈150-175 kg/month reduction); Investment: High (capital equipment + operational costs); Payback period: 3-4 years, with significant worker health protection benefits.

Combining Scenario 1 and 2 provides optimal cost-effectiveness, potentially reducing VOC emissions by 60-70% (≈224 kg/month) while improving workplace safety and reducing waste generation. Furthermore, based on average solid B3 waste data exiting TPS and transported by third parties during the period January to April 2025, it is known that volatile organic compound (VOC) emission potential reaches approximately 374,35 kg per month. This figure is obtained from the accumulation of various types of solid waste containing easily evaporating residues, such as oil-contaminated rags, used filters, used oil hoses, and sludge from oil traps. Among all types of waste, contaminated rags become the largest VOC emission contributor as explained in the table, at approximately 254,8 kg per month, followed by contaminated filters with a contribution of 83,23 kg per month as detailed in Table 4. This shows that waste originating from cleaning activities and spare part replacement plays a significant role in producing air pollutants.

Table 4. Average VOC emissions

No	Type of B3 Waste	Average Production (Tons/month)	VOC Emission Factor (Kg/Ton)	Average VOC Emissions (Kg/Month)
1	Contaminated Rags	12,74	20	254,80
2	Contaminated Filters	11,89	7	83,23
3	Contaminated Hoses	4,46	7	31,22
4	Used Batteries	4,37	0	0,00
5	Sludge	1,02	5	5,10
	Average VOC Total			**374,35 kg/ month**

Based on this data, VOC emission control focus should be prioritized on waste types with the largest contribution, especially rags and contaminated oil filters. Mitigation steps such as improving closed storage systems, reducing waste quantities through material efficiency, and further processing can be effective strategies. With this understanding, companies can develop more targeted waste management plans and meet applicable environmental standards.

During the period January to April 2025, unit repair activities generated large amounts of liquid B3 waste, namely 601 tons of used lubricants and 33,07 tons of chemical waste, as shown in Table 5. The amount of used lubricants reaching an average of 150,25 tons per month is very high and reflects the intensity of heavy equipment activities using oil and lubricants. Chemical waste, although smaller in quantity, remains high risk due to its toxic, corrosive, or reactive nature. Both types of waste potentially pollute soil and water sources if not managed properly, and endanger human health through direct contact, hazardous vapors, or accumulation of toxic substances that can cause irritation, organ disorders, and even cancer risks.

Therefore, management of this waste requires serious attention for the sake of environmental preservation and worker safety.

Table 5. Liquid B3 Waste Generated

No	Type of B3 Waste	Liquid B3 Waste Generated (Tons)					
		Jan-25	**Feb-25**	**Mar-25**	**Apr-25**	**Average**	**Total (Tons)**
1	Used Lubricants	168	149	143	141	150,25	601
2	Chemical Waste	9,41	5,66	16	2	8,2675	33,07

This reflects a relatively stable waste production pattern from unit repair activities, with small variation between months.

Based on the previous approach (and supported by EPA & EMEP/EEA), VOC emission factors for used lubricants in closed tanks range: 0,5 – 2,0 kg VOC per ton of used lubricants per month.

In this study, a conservative middle value is used: 1,0 kg VOC/ton/month. Therefore, the monthly VOC Liquid Waste calculation stored is: 150,25 tons × 1 kg VOC = 150,25 kg VOC/month.

The amount of used oil waste generated from heavy equipment maintenance activities has a direct relationship with the magnitude of volatile organic compound (VOC) emissions released to the environment. Used oil, especially that which has not undergone further processing, contains easily evaporating light hydrocarbon fractions, such as aromatics and aliphatics. The larger the volume of stored oil waste, especially over a long period, the potential for VOC emissions also increases even though storage is done in closed tanks. In this study, it is known that from an average oil waste production of 150,25 tons per month, estimated VOC emissions reach approximately 150,25 kg/month with a conservative emission factor of 1,0 kg VOC per ton of oil.

3.1. Life Cycle Inventory

Heavy equipment repair processes are an important component in Life Cycle Inventory analysis covering various aspects of operational inputs and outputs (Wolff et al., 2020). Table 6 below shows data related to heavy equipment repair processes in the context of Life Cycle Inventory (LCI). This table includes inputs and outputs related to emissions generated during heavy equipment repair processes, including diesel use and CO2 emissions produced from vehicles and generators. This data provides an overview of environmental influences occurring during heavy equipment repair operational activities.

Table 6. LCI Heavy Equipment Repair Process

Input	**Amount (Per Month)**
Diesel generated in repairs	225 liters (0,188 tons)
Diesel generated for generators	13.548 liters (11,31 tons)
Output	Amount (per month)
Direct CO_2 emissions (vehicles)	596,25 kg CO_2/ month
Direct CO2 emissions (generators)	35.907,2 kg CO_2/ month

Each month, heavy equipment repairs activities require 225 liters or equivalent to 0,188 tons of diesel for vehicle operations, while to support generator operations requires 13.548 liters or 11,31 tons of diesel. This energy consumption produces significant environmental impacts in the form of direct CO2 emissions. Emissions generated from vehicles reach 596,25 kg CO2 per month, while emissions from generators are much higher at 35.907,2 kg CO2 per month. This significant difference shows that generator use is the main contributor of CO2 emissions in heavy equipment repair processes.

B3 Waste storage processes also become an integral part of LCI analysis with complex characteristics. The table shows details of B3 Waste storage processes including monthly inputs and outputs. Inputs include various materials such as used oil waste, generator electrical energy, cleaning water, cleaning chemicals, and solid waste. Meanwhile, outputs include VOC emissions to air and indirect emissions in the form of CO_2 generated from these processes. Each element in this table is explained with the amount produced each month, accompanied by relevant notes.

Table 7. LCI B3 Waste Storage Process

Input	**Amount (Per Month)**
Used Oil Waste	150,25 Tons
Generator Electrical Energy	13548 liters (11,31 Tons)
Water (Cleaning)	6000 liters
Cleaning Chemicals	200 liters
Solid Waste (Absorbent, Filters, Hoses, etc.)	34,24 Tons
Output	Amount (Per Month)
VOC emissions to air	502,08 Kg VOC/Month
Indirect emissions (CO_2 Generator)	35.907,2 kg CO_2/Month

B3 Waste storage processes involve management of various types of waste with quite large volumes each month. The main input in this process is used oil waste of 150,25 tons requiring special handling. To support storage facility operations, electrical energy from generators is used with diesel consumption the same as in heavy equipment repair processes, namely 13.548 liters or 11,31 tons per month. Storage facility cleaning processes require 6.000 liters of water and 200 liters of cleaning chemicals each month. In addition, there is solid waste in the form of absorbent, filters, hoses, and other components totaling 34,24 tons that must also be managed properly. Environmental impacts from B3 Waste storage processes include VOC emissions released to air of 502,08 kg per month and indirect CO2 emissions from generator operations of 35.907,2 kg per month.

3.2. Life Cycle Impact Assesment (LCIA)

Life Cycle Impact Assessment (LCIA) is an important stage in life cycle analysis that evaluates potential impacts of various B3 waste management activities on the environment and human health. In the context of B3 waste management, there are several main impact categories that need to be analyzed comprehensively. Global Warming Potential is a key indicator in evaluating the contribution of B3 waste management activities to global climate change. Based on 3 B3 waste Management activities focusing on CO_2 Emissions data, their GWP values can be determined. Following are monthly GWP calculations based on CO_2: (1) CO_2 Emissions from Unit Repair Activities from unit repair vehicles: 596,25 kg CO_2; (2) CO_2 Emissions from B3 Waste Storage Activities from generators: 35.907,2 kg CO_2; (3) Total GWP (All activities) = 596,25 kg CO_2 + 35.907,2 kg CO_2 = 36.503,25 kg CO_2/month. Using the IPCC standard emission factor of 2,65 kg CO_2 per liter of diesel, the total greenhouse gas (GHG) emissions generated in one month is kg CO_2e. This GWP reflects the global warming potential generated.

In addition to operational activity data, laboratory measurement results on ambient air around the B3 Waste TPS shown in Table 8 indicate the presence of CO_2 gas (405 ppm) and CO (788 µg/m³), which when converted produces GWP of approximately 730,5 kg CO_2e per month as explained in the table. This contribution is relatively small, only about 1,65% of total monthly GWP sourced from operational activities.

Table 8. GWP Values

No	Parameter	Concentration	Estimated Mass (kg)	GWP Factor (CO_2-eq)	GWP Value (kg CO_2-eq)
1	CO_2	405 ppm (~729.000 µg/m³)	729,00	1	729,00
2	CO	788 µg/m³	0,788	1,9	1,50
Total			**729,79**		**730,50**

Based on calculations, total greenhouse gas (GHG) emissions from all B3 waste management activities reach 44,3 tons CO_2e per month, while contribution from ambient air is only about 0,73 tons CO_2e per month or 1,65% of total emissions. If compared with GHG emission reporting thresholds set by US EPA and GHG Protocol guidelines, namely 10.000 tons CO_2e per year (≈833 tons CO_2e per month) as a large facility scale, then the value of 44,3 tons CO_2e/month is far below this threshold and falls into the low impact category. According to Indonesian Government Regulation No. 101/2014 on Hazardous and Toxic Waste Management, facilities generating GHG emissions below 100 tons CO_2e/month from waste management activities are classified as "small-scale emitters" not requiring carbon credit mechanisms but still subject to environmental monitoring requirements.

These results are also consistent with studies in the Carbon Management journal (Rogelj et al., 2016) which classifies emissions below 100 tons CO_2e/month as small contributions to global warming when compared with industrial-scale energy or transportation sectors. Comparative analysis with similar studies shows that heavy machinery manufacturing in Turkey (Üçtuğ et al., 2025) reported 150–300 tons CO_2e per unit produced, which is significantly higher than our monthly operational emissions. Meanwhile, biogas-powered generator systems produce 6,3 tons CO_2e per day (approximately 189 tons per month), while coal systems reach 19,6 tons CO_2e per day (around 588 tons per month) (Kumawat et al., 2024), both exceeding our facility's emissions. In addition, mining vehicle maintenance operations in comparable coal mining contexts report 50–80 tons CO_2e per month (Wardhani et al., 2023), placing PT PPA's emissions in the lower range of industry benchmarks. Thus, B3 waste management activities at this location can be said to have low global warming potential, where main emissions are primarily contributed by vehicle and generator fuel combustion.

Global Warming Potential is a measure of the potential of greenhouse gases (GHG) such as CO_2, CH_4, and N_2O in trapping heat in the atmosphere, which contributes to global warming. Increased GWP accelerates climate change, triggering extreme temperatures, unpredictable weather patterns, sea level rise, and ecosystem damage. These environmental impacts affect natural resource sustainability, disrupt water cycles, reduce biodiversity, and worsen overall environmental quality.

Photochemical Ozone Creation Potential (POCP) becomes another important parameter in evaluating environmental impacts. POCP is a measure of a substance's potential, especially volatile organic compounds (VOC) and nitrogen oxides (NOx), in forming tropospheric ozone (ground-level ozone) through photochemical reactions in the atmosphere (Andersson-Sköld et al., 1992). This tropospheric ozone is the main cause of smog and impacts human health and ecosystems. Based on analysis results, there are 2 waste management activities that have POCP potential, namely waste Storage activities, because these processes produce VOC emissions to air generated from the waste produced.

Table 9 presents estimated emission data of compounds contributing to tropospheric ozone formation in units of kg C2H4-eq from B3 Waste management activities. There are main emission sources, namely VOC from B3 waste storage. VOC emissions from VOC storage of 602.50 kg C2H4-eq indicate significant potential for photochemical haze formation.

Table 9. POCP Values

Emission Source	Emissions (kg)	POCP Conversion Factor (kg C2H4-eq/kg)	POCP (kg C2H4-eq)
VOC – B3 Waste Storage	502,08	1,2	602,50
Total	**502,08**	**-**	**602,50**

A total POCP value of ≈602.50 Kg C_2H_4 -eq per month originating from VOC and NO_x emissions in B3 waste management shows relatively low to medium tropospheric ozone formation potential. According to Andersson-Sköld et al. (1992) study, compounds such as alkenes and aromatics with high POCP are classified as medium to high ozone producers, while simple aliphatic and halogenated compounds generally fall into the low to medium category.

Comparative benchmarking for POCP shows that vehicle maintenance facilities in urban areas typically report POCP values of 800–1.500 kg C_2H_4-eq per month due to higher VOC emissions from spray painting and solvent use. Industrial coating operations can generate 2.000–5.000 kg C_2H_4-eq per month, significantly exceeding our values. According to the European Environment Agency (EEA), POCP values below 1.000 kg C_2H_4-eq per month are classified as "low concern" for regional air quality when proper containment measures are in place.

In this context, POCP figures below 2 tons ethylene equivalent per month are still far below levels considered significant for regional policy control (namely measurements in thousands of kg per week or tens of thousands of kg per year). Therefore, although VOC emissions are quite high in absolute terms (≈1.033 kg VOC), after conversion to C_2H_4-eq this value is still within the low to moderate category bounds, not the high category that typically reaches tens or hundreds of kg C_2H_4-eq daily as commonly used in urban air quality studies and large industrial scenarios.

From a human health perspective, high POCP causes increased ozone concentrations in ambient air, which can trigger respiratory irritation, worsen lung diseases (such as asthma and bronchitis), and reduce lung function (Sundari et al., 2023). Long-term tropospheric ozone exposure can also increase cardiovascular disease risks. Therefore, emission control from main sources such as motor vehicles, generators, and VOC-based liquid waste becomes an important step to reduce POCP values and minimize environmental and health risks (Rusdiana et al., 2020).

Ecotoxicity Potential is a crucial aspect in environmental impact evaluation that needs special attention. Ecotoxicity Potential measures the potential of a substance or activity to cause damage to non-human organisms, especially in water, soil, and air, caused by heavy metals, toxic chemicals, and hazardous organic compounds. This category is very relevant for B3 (Hazardous & Toxic Materials) Waste, Heavy metal release (Cd, Pb, Cr), Technical chemicals (VOC, solvents, cleaners). Following are data that can be used in B3 waste management activities, namely metal content of air around B3 waste TPS: (1) Cadmium (CD) = 0,004 mg/m³; (2) Manganese (Mn) = 0,005 mg/m³; (3) Lead (Pb) = 0,002 mg/m³. In addition, solid waste & used oil data are also needed including: (1) solid waste = 34,24 Tons; (2) used oil waste

= 150,25 Tons. As well as cleaning chemical data of 200 liters/month. Following is specific analysis of potential impacts explained in Table 10 and with risk assessment explained in Table 11.

Table 10. Ecotoxic Impacts

Potential Source	Substance/Chemicals	Exposed Media	Ecotoxic Impact
Air around TPS	Pb, Cd, Mn (heavy metals)	Air, Soil	Toxic to small animals, plants, microorganisms
Solid waste	Filters, absorbent, spare parts	Soil, Water	Contains oil/metals → poison to soil/water biota
Used oil waste	Aromatic hydrocarbons, heavy metals	Soil, Water	Chronic effects on aquatic flora-fauna
Chemical cleaners	Detergent, solvents, surfactants	Water, Soil	Eutrophication, microbial ecosystem disturbance
VOC emissions	Benzene, Toluene, Xylene	Air, Soil	Toxic to microorganisms, ecosystem disturbance

Table 11. Ecotoxic Risk Status

Parameter	Value	Threshold	Risk Status
Cadmium (Cd)	0.004 mg/m^3	< 0.01 mg/m^3	⚠️ Low but significant
Lead (Pb)	0.002 mg/m^3	< 0.5 mg/m^3	✅ Safe, monitored
Total Hazardous Waste	>180 tons/month	-	⚠️ High potential if leaked
Cleaning Chemicals	200 liters/month	-	⚠️ Requires liquid waste disposal procedures

To strengthen the ecotoxicity analysis, the following comparison with environmental quality standards is provided:

Table 12. Heavy Metal Concentrations vs. Regulatory Thresholds

Parameter	Measured Value	WHO Air Quality Guideline	Indonesian Standard (PP 22/2021)	Risk Status
Cadmium (Cd)	0,004 mg/m^3	0,005 mg/m^3 (annual)	0,01 mg/m^3	✅ Below limits but requires monitoring
Lead (Pb)	0,002 mg/m^3	0,0005 mg/m^3 (annual)	0,002 mg/m^3	⚠️ At regulatory limit
Manganese (Mn)	0,005 mg/m^3	0,15 mg/m^3 (annual)	0,15 mg/m^3	✅ Well below limits

The analysis indicates that cadmium, measured at 0,004 mg/m^3, represents 80% of the WHO guideline value (0,005 mg/m^3) and 40% of the Indonesian standard, remaining technically compliant but close to the WHO limit, which suggests potential bioaccumulation risks with chronic exposure. Classified by IARC as a Group 1 carcinogen, cadmium therefore requires continuous monitoring even at sub-threshold concentrations. Lead, at 0,002 mg/m^3, equals the Indonesian regulatory limit yet exceeds the WHO's stricter guideline (0,0005 mg/m^3) by fourfold; since lead has no safe exposure threshold for neurodevelopmental effects, particularly among vulnerable populations, enhanced control measures are warranted. Manganese, recorded at 0,005 mg/m^3, accounts for only 3.3% of regulatory limits, indicating effective containment, though manganese neurotoxicity can still occur under long-term occupational exposure, necessitating worker health surveillance.

Comparing with soil and water quality standards under Indonesian Government Regulation No. 22/2021, the hydrocarbon contamination potential from used oil, which contains Total Petroleum Hydrocarbons (TPH) of 5.000–15.000 mg/kg, could exceed soil quality standards (100 mg/kg for sensitive ecosystems) by 50–150 times if leakage occurs. Meanwhile, surfactant concentrations in cleaning chemicals, typically 10–30% w/w, can induce aquatic toxicity at LC50 levels of 1–10 mg/L for sensitive fish species, far below concentrations expected during accidental spills.

While airborne heavy metal concentrations remain within regulatory compliance, the ecotoxicity potential from stored waste (>180 tons/month) presents significant environmental risks requiring robust secondary containment, spill prevention protocols, and regular environmental monitoring as specified in Indonesian regulations.

Ecotoxicity Potential is an impact indicator measuring the potential of chemicals or pollutants to damage ecosystems, both aquatic (water) and terrestrial (soil) organisms. This impact is often caused by toxic compounds such as heavy metals (Pb, Cd, Mn), pesticides, aromatic hydrocarbons, and chemical compounds from B3 waste that can pollute water, soil, or sediment. These toxic substances can disrupt food chains, inhibit microorganism growth, cause bioaccumulation in fish, and trigger long-term damage to biodiversity.

ETP can impact humans through indirect pathways, such as water, soil, and food chain pollution. Hazardous pollutants such as heavy metals (Pb, Cd, Hg) and aromatic hydrocarbons from B3 waste can accumulate in plants or aquatic animals consumed by humans, thus triggering chronic poisoning, organ damage (liver, kidneys, nerves), to carcinogenic effects. In addition, groundwater or river contamination due to waste spills can also cause health disturbances such as skin diseases, respiratory disorders, and immune system disorders if exposed over the long term.

Particulate Matter Formation Potential (PMFP) is an equally important impact category in comprehensive analysis. PMFP is one of the impact categories in LCIA that measures activity contributions to fine particle formation (PM10 and PM2.5) that impact Human respiratory disturbances (asthma, lung infections), Premature mortality risk, Damage to plants and air ecosystems with units of kg PM10-equivalent (kg PM10-eq). Based on analysis of data already possessed, two main sources of particulate formation can be determined based on Indirect emissions from fuel combustion (diesel) in vehicles, generators, and waste transport trucks and Particulate emissions from ambient air, recorded in laboratory results. Following are detailed data, from diesel consumption data detailed by activities in Table 13.

Table 13. PMFP Diesel Consumption

Activity Source	Diesel Consumption (liters/month)
Operational vehicles	225 liters
B3 TPS Generator	13.548 liters
Total	13.773 liters

Using PM10 emission factors from CML & ReCiPe literature: Average emission factor: 0,001 kg PM10-eq/liter diesel, then PMFP from diesel = 13.773 Liters × 0,001 kg

PM10-eq/liter diesel = 13.773 kg PM10-eq. Meanwhile, if calculated using laboratory result data in Table 14.

Table 14. PMFP Analysis from Air Data

Parameter	Value	Unit
PM10	32,53 µg/m³	= 0,03253 mg/m³
PM2.5	6,68 µg/m³	= 0,00668 mg/m³
Total dust	4,7 mg/m³	mg/m³

Assumption of environmental air volume: 1.000 m³/day × 30 days = 30.000 m³/month, using PM10 emission factors from CML & ReCiPe literature

Average emission factor: 0,001 kg PM10-eq/liter, then calculation of PM mass from ambient air: (1) PM10: 0,03253 mg/m³×30.000 m³ = 975,9 mg = 0,976 g = 0,000976 kg; (2) PM 2,5: 0,00668 mg/m³×30.000 m³ = 200,4 mg = 0,2004 g = 0,000200 kg; (3) Total Dust: 4,7 mg/m³×30.000 m³ = 141.000 mg = 141 g = 0,141 kg

Therefore, Total Particulate Matter Formation Potential, following Table 15 details emission sources and PM 10 values according to calculations.

Table 15. PM 10-eq Values

Source	PM10-eq Value (kg/month)
Emissions from diesel combustion	13.773
PM10 from ambient air	0,000976
PM2.5 from ambient air	0,000200
Total dust (non-PM10-eq)	0,141
Total PMFP (conservative)	≈ 13,92

Total diesel consumption from all activities reaches 13.773 liters per month. Using a characterization factor of 0,001 kg PM10-eq per liter of diesel (based on CML 2001 and ReCiPe methods), the estimated PMFP from fuel combustion reaches 13.773 kg PM10-eq per month. Laboratory measurement results show that average PM10 value is 32,53 µg/m³ and PM2.5 is 6,68 µg/m³. With an air volume assumption of 30.000 m³ per month, particulate emissions from ambient air are: PM 10: 0,000976 Kg, PM 2,5 = 0,000200 kg, Total dust (Non PM Specific) = 0,141 K. Although particle contribution from ambient air quantitatively is smaller compared to combustion emissions, this data strengthens the existence of particulate accumulation around the operational area. Thus, total PMFP obtained from both approaches is 13,92 kg PM10-eq per month. This value shows that operational activities make significant contributions to air pollution potentially affecting worker and community health around the activity area. This is also elaborated in Table 16.

Total PMFP value ≈ 13,92 kg PM10 eq/month, consisting of 13.773 kg from diesel combustion plus approximately ≈ 0,15 kg from ambient air particles, falls into the low to moderate category, considering this value is very small when compared with large industrial scale. For example, in an LCA biogas-versus-coal study by Kumawat et al. (2024), generator systems produce up to 6.314 kg PM10 eq in one system as the midpoint study result, while coal systems reach 19.630 kg PM10 eq, far exceeding our figure of 13,92 kg PM10-eq/month.

Comparative analysis with recent studies shows that heavy machinery manufacturing by Üçtuğ et al. (2025) reported a PMFP of 2.500 to 4.000 kg PM10-eq per production unit, indicating that manufacturing processes generate 180 to 287 times more particulate matter than our monthly operations. Mining vehicle operations analyzed by Wardhani et al. (2023) in coal mining heavy equipment workshops recorded 25 to 40 kg PM10-eq per month, placing PT PPA's values at approximately 35 to 56 percent of comparable facilities, suggesting relatively effective emission controls. In terms of compliance, Indonesian ambient air quality standards under PP 22/2021 set PM10 at 70 µg/m³ (24-hour) and PM2.5 at 55 µg/m³, while our measured values (PM10 at 32.53 µg/m³ and PM2.5 at 6,68 µg/m³) are well within limits, corresponding to 46% and 12% of the standards respectively.

Table 16. PMFP Results

No	Emission Source	Parameter	Emission Value	PMFP Factor (kg PM10-eq/unit)	PMFP Result (kg PM10-eq)
1	Diesel consumption (operational)	13.773 Diesel:	—	0,001 per liter	13.773
2	Ambient Air – PM10	0,03253 mg/m³	30.000 m³	—	0,000976
3	Ambient Air – PM2.5	0,00668 mg/m³	30.000 m³	—	0,000200
4	Ambient Air – Total dust	4,7 mg/m³	30.000 m³	—	0,141
	Total				**13,92**

Fine particle formation values in other industries also often reach thousands of kilograms per year or hundreds of kg PM10 eq per month according to ReCiPe or CML methods. Thus, your value of 16–17 kg PM10 eq/month is still below 1% of large industry values, which indicates relatively small and still controlled particulate formation potential, although regular monitoring is still needed to ensure air quality remains safe around operational locations.

PMFP describes an activity's potential to produce fine particles ($PM_{2.5}$ and PM_{10}) that can settle in ambient air. Main PMFP sources come from fossil fuel combustion in generators, waste transport vehicles, and B3 waste transfer processes that generate dust. These fine particles can reduce air quality, worsen visibility (haze), and pollute ecosystems through deposition on water surfaces and soil. In the long term, particulate accumulation can also damage vegetation, reduce plant productivity, and accelerate soil acidification processes.

From a human health perspective, $PM_{2.5}$ and PM_{10} are hazardous pollutants because their very small size allows them to enter deep into respiratory tracts and even penetrate the circulatory system. Long-term exposure to fine particulates can cause cardiovascular diseases, chronic lung disorders, asthma, to lung cancer. Children, elderly, and people with respiratory diseases become the most vulnerable groups. Therefore, monitoring PM levels in ambient air and using emission control technology in vehicles and generators become important mitigation steps to suppress PMFP.

Based on Life Cycle Assessment analysis results conducted, there are several important findings and strategic recommendations that need to be implemented in B3 waste management. Global Warming Potential analysis shows that greenhouse gas (GHG) emissions mainly come from diesel use in operational vehicles and generators at B3 Waste TPS, with total contribution of about 36.5 tons CO_2e per month. This value is relatively low when compared with GHG emission reporting thresholds for large-scale facilities (Intergovernmental Panel on Climate Change (IPCC), 2019; Kumawat et al., 2024; Rogelj et al., 2016). However, these emissions still contribute to global climate change. Therefore, mitigation efforts need to focus on fuel use efficiency, partial energy replacement with renewable sources (e.g., small-scale solar power), and improvement of low-emission combustion technology.

Evaluation of Volatile Organic Compounds (VOC) emissions reveals that contaminated rags and used oil filters are the main VOC emission contributors with average total of about 374 kg/month. These emissions potentially pollute air and have implications for worker and surrounding community health. Control strategies can be done through closed storage systems, source waste generation reduction by replacing disposable materials, and pre-treatment application such as activated carbon adsorption to suppress volatile compound release.

In the context of Photochemical Ozone Creation Potential (POCP), analysis shows POCP value of ±602,5 kg C_2H_4-eq/month comes from VOC emissions in waste storage processes. Although still in the low to medium category, tropospheric ozone formation potential needs to be anticipated because it can increase respiratory disorder risks. Mitigation efforts can be done by strengthening ventilation systems and air quality monitoring, and minimizing VOC exposure through chemical substance substitution with low-volatile alternatives.

Ecotoxicity Potential (ETP) aspects require special attention because ecotoxicity potential was identified from the presence of heavy metals (Cd, Pb, Mn), hydrocarbon residues in solid and liquid waste, and cleaning chemicals. These substances potentially pollute soil and water, and cause toxic effects on aquatic and terrestrial organisms. To suppress risks, companies need to implement secondary containment in storage facilities, strengthen spill emergency response procedures, and implement routine monitoring programs on environmental media (groundwater, sediment, and air).

Particulate Matter Formation Potential (PMFP) analysis shows total PMFP value of 13,92 kg PM10-eq per month, dominated by diesel combustion in generators and operational vehicles. Although relatively low compared to large industrial sectors, fine particles still pose long-term health risks. Relevant recommendations include regular machine maintenance to suppress emissions, use of low-sulfur fuels, and study of diesel particulate filter (DPF) technology application in vehicles and generators.

This LCA study, while comprehensive, has several limitations that should be acknowledged. The temporal scope covered only four months (January to April 2025), which may not capture full seasonal variations or annual operational cycles in mining activities. Extended monitoring across both wet and dry seasons would provide more robust baseline data. The system boundary constraints of the cradle-to-gate approach also exclude downstream processes such as waste transportation to final disposal facilities, treatment at licensed third-party facilities, and the ultimate fate of materials; hence, a complete cradle-to-grave assessment would provide a fuller picture of environmental impacts. Emission factor uncertainties remain since conservative mid-range emission factors from international literature such as EMEP/EEA and the US EPA were applied, and site-specific emission measurements through direct sampling and analysis would reduce current uncertainty ranges estimated at ±20–30%. Some impact categories such as water consumption impacts, land use changes, and resource depletion were not quantified due to data availability constraints and scope limitations. Furthermore, the absence of cost-benefit analysis for the proposed mitigation strategies limits the decision-making support for management.

The implementation of mitigation actions also faces several technical, operational, and regulatory challenges. Technical constraints include limited availability of renewable energy infrastructure in remote mining locations, high capital costs for advanced emission control technologies such as VOC recovery systems and diesel particulate filters, and the need for specialized expertise in hazardous waste pre-treatment processes. Operationally, the company must maintain continuous 24-hour operations while implementing equipment upgrades, ensure worker compliance with new waste handling procedures, and balance productivity demands with environmental performance improvements. From the regulatory perspective, evolving Indonesian environmental regulations require adaptive management systems, while coordination among multiple stakeholders including mining authorities, environmental ministries, and local governments adds complexity, along with documentation and reporting obligations for ESG disclosure.

Future research directions should include an extended LCA scope by conducting cradle-to-grave assessments that incorporate waste transportation and final treatment, integrating social LCA to evaluate worker health impacts and community benefits, and performing economic input-output LCA to capture supply chain effects. Site-specific data collection is also essential through direct measurement of VOC emissions using portable analyzers, continuous ambient air monitoring with real-time sensors, and soil and groundwater sampling around TPS to validate ecotoxicity models. Further studies should assess new technologies, including pilot testing of closed-loop lubricant recycling systems, feasibility analysis of solar-diesel hybrid generators, and evaluation of biodegradable cleaning chemicals as substitutes. Comparative studies are also recommended to benchmark with other mining contractors in Indonesia, conduct cross-sector comparisons with manufacturing and transportation industries, and examine international best practices from mining operations in Australia, Canada, and South Africa.

Digital integration offers another key direction through the development of real-time LCA monitoring dashboards using IoT sensors, machine learning models for predictive emission forecasting, and blockchain-based waste tracking for enhanced transparency. Policy impact assessments are also needed to analyze the implications of carbon pricing mechanisms on operational costs, evaluate incentive structures for green technology adoption, and assess ESG reporting requirements for competitive positioning.

Several knowledge gaps require further attention, including the long-term fate and transport of heavy metals in tropical mining soils, bioaccumulation factors for local aquatic species in mine-affected watersheds, health impact assessments of chronic low-level VOC exposure on mining workforces, and integration of life cycle costing (LCC) with environmental LCA for holistic sustainability evaluation. Addressing these challenges and research gaps will strengthen the scientific foundation for environmental management optimization and support PT PPA’s transition toward more sustainable mining operations aligned with circular economy principles and net-zero emissions targets.

From corporate and ESG perspectives, strategically, these LCA study results function not only as a technical instrument to map environmental impacts, but also become the foundation in strengthening company reputation through Environmental, Social, and Governance (ESG) principles application. Transparent publication of LCA results can increase stakeholder trust and strengthen company image as an innovative and responsible mining contractor.

This study’s findings and recommendations directly support several United Nations Sustainable Development Goals. In relation to SDG 12: Responsible Consumption and Production, particularly Target 12,4, which aims to achieve environmentally sound management of chemicals and all wastes throughout their life cycle in accordance with international frameworks and to reduce their release to air, water, and soil, PT PPA contributes through the implementation of systematic B3 waste management with licensed TPS facilities, achieving more than 95% waste containment efficiency and maintaining emissions below regulatory thresholds. The proposed VOC reduction strategies, with a 60 to 70% reduction potential, directly advance this target.

Under SDG 13: Climate Action, aligned with Target 13,2 that calls for the integration of climate change measures into national policies, strategies, and planning, PT PPA's quantification of GHG emissions at 44,3 tons CO_2e per month provides a baseline for carbon management. The recommended energy efficiency improvements and adoption of renewable energy technologies further support Indonesia's Nationally Determined Contributions under the Paris Agreement.

In the context of SDG 3: Good Health and Well-Being, specifically Target 3.9, which seeks to substantially reduce deaths and illnesses resulting from hazardous chemicals and pollution, PT PPA's initiatives in PMFP reduction through emission controls and VOC containment directly protect worker and community health. Ongoing heavy metal monitoring enables early detection of exposure risks and supports preventive occupational health strategies.

For SDG 9: Industry, Innovation, and Infrastructure, corresponding to Target 9.4, which emphasizes upgrading infrastructure and retrofitting industries to make them sustainable through clean and efficient technologies, PT PPA's application of LCA-based optimization represents an innovative approach to environmental management in industry. The proposed technological upgrades, including solar-diesel hybrid systems, VOC recovery technologies, and closed-loop recycling mechanisms, promote sustainable infrastructure development within the mining sector.

Finally, SDG 15: Life on Land, and particularly Target 15,3 which focuses on combating desertification and restoring degraded land to achieve a land-degradation-neutral world, is addressed through PT PPA's ecotoxicity risk management and spill-prevention protocols. These measures protect terrestrial ecosystems from heavy metal and hydrocarbon contamination, contributing to the preservation of land quality in mining regions.

By aligning the LCA findings with these specific SDG targets, PT PPA demonstrates measurable contributions to global sustainability frameworks, thereby strengthening corporate accountability and enhancing stakeholder engagement in ESG performance reporting.

4. CONCLUSIONS AND RECOMMENDATIONS

This study shows that application of Life Cycle Assessment (LCA) method with Cradle-to-Gate approach is able to provide a comprehensive picture regarding potential environmental impacts from heavy equipment repair activities and B3 waste storage. Analysis results identify that main sources of environmental impacts come from solid waste generation (especially contaminated rags and used oil filters), used lubricant liquid waste volume, and diesel-based energy use in operational vehicles and generators. Based on Life Cycle Impact Assessment (LCIA) results, largest contributions to environmental impact categories include: (1) greenhouse gas emissions (GWP) of ±44,3 tons CO_2e per month with dominance from diesel consumption, (2) average VOC emissions of 374 kg/month with main source of contaminated rags, (3) tropospheric ozone formation potential (POCP) of ±602,5 kg C_2H_4-eq/month, (4) ecotoxicity potential due to heavy metals, hydrocarbons, and cleaning chemicals, and (5) contribution to Particulate Matter Formation Potential (PMFP) of 13,92 kg PM10-eq per month.

Although emission values and potential impacts generated are classified in the low to moderate category when compared with large industrial sectors, this classification is substantiated through: (1) comparison with Indonesian regulatory thresholds (Government Regulation No. 101/2014 for B3 waste, PP 22/2021 for air quality), where all parameters remain within compliance limits; (2) benchmarking against international studies showing PT PPA's GWP is 80% lower than comparable biogas generator facilities (Kumawat et al., 2024) and PMFP is 56% lower than similar mining workshops (Wardhani et al., 2023); and (3) assessment against WHO air quality guidelines, with PM10 and PM2.5 concentrations at 46% and 12% of limits respectively. Nevertheless, the existence of environmental hotspots in B3 waste management activities still requires special attention, particularly for VOC emissions from contaminated rags (252 kg/month) and potential ecotoxicity risks from heavy metals approaching WHO guideline thresholds.

Application of mitigation strategies such as energy efficiency, use of closed storage systems, waste pre-treatment, used lubricant recycling programs, and strengthening environmental monitoring systems can be optimal steps to suppress arising impacts. Integrated implementation of proposed mitigation scenarios could achieve: (1) 60-70% reduction in VOC emissions (≈224 kg/month reduction), (2) 15-20% reduction in GHG emissions through energy efficiency improvements (≈6.6-8.9 tons CO_2e/month reduction), (3) 30% reduction in solid waste generation through source minimization (≈10.3 tons/month), and (4) enhanced ecotoxicity risk management through secondary containment and monitoring protocols.

Strategically, these study results not only provide technical information for companies in environmental management, but also contribute to corporate image strengthening through Environmental, Social, and Governance (ESG) principles application and support Sustainable Development Goals (SDGs) achievement. Thus, PT PPA can position itself as a mining company that is not only oriented toward productivity, but also toward environmental sustainability and social responsibility. In summary, PT PPA's implementation roadmap emphasizes a phased approach that integrates environmental performance with operational continuity. In the short term, the company will focus on practical steps such as installing sealed VOC-filtered waste drums, training workers in waste minimization, monitoring ambient air quality, and conducting spill-response drills. Medium-term priorities include testing reusable materials, evaluating solar-diesel hybrid generators, digitalizing waste tracking, and partnering with licensed recyclers. Long-term strategies involve installing VOC recovery systems, introducing renewable energy to replace 30 percent of diesel use, upgrading equipment to Euro V standards, obtaining ISO 14001 certification, and embedding LCA results into ESG reporting. Progress will be ensured through quarterly LCA updates, annual external audits, active stakeholder communication, and adaptive management in response to regulatory and technological changes. Collectively, these actions position PT PPA to achieve measurable environmental gains, maintain operational efficiency, and reinforce its leadership in sustainable mining within Indonesia.

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