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Research Article

Life Cycle Assessment (LCA) of Methane Capture Implementation Scenario in Palm Oil Mill Effluent (POME) Treatment

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Abstract. The palm oil industry plays a strategic role in the Indonesian economy as a major global exporter of vegetable oils. Crude Palm Oil (CPO) is extensively utilized in the food, pharmaceutical, and energy sectors. Despite its economic importance, CPO production generates Palm Oil Mill Effluent (POME), a liquid waste. POME is commonly treated using open pond systems, where anaerobic degradation of organic matter leads to methane emission, contributing to climate change and adverse human health impacts. Methane capture has been proposed as an effective mitigation strategy to reduce methane emissions from POME treatment. However, its environmental performance requires an evaluation. This study assesses the environmental impacts of POME treatment under business-as-usual conditions and methane capture implementation scenarios with capture efficiencies of 20%, 50%, and 80% using the Life Cycle Assessment (LCA) methodology. A gate-to-gate system boundary was applied with a declared unit of 1 kg of CPO produced. Environmental impact calculations were performed using openLCA version 2.5.0 with the Ecoinvent v3.11 database as secondary data. The results indicate that increasing methane capture efficiency leads to a consistent reduction in environmental impacts, particularly in the Global Warming Potential (GWP) and Photochemical Ozone Formation Potential (POFP) categories. Methane emissions have the significant role in exacerbating greenhouse gas effects and facilitating tropospheric ozone formation. In conclusion, this study demonstrates the potential of methane capture implementation to enhance the environmental performance of the palm oil industry and supports its consideration as a sustainable mitigation strategy.

Keywords: Crude Palm Oil (CPO); Life Cycle Assessment (LCA); Methane Capture; Palm Oil Industry; Palm Oil Mill Effluent (POME)

1. Introduction

The palm oil industry is a pivotal sector within the Indonesian economy, as it contributes to foreign exchange earnings and plays a crucial role in meeting global vegetable oil needs. Indonesia has maintained its position as the world's leading exporter of Crude Palm Oil (CPO), contributing approximately 54.81% of total global palm oil exports in 2023, more than twice that of other major producing countries, including Malaysia (Zhang et al., 2025). Furthermore, data from Statistics Indonesia (BPS) shows that the area of land used for palm plantations increased by 8.2% and 0.42% between 2021 and 2023, respectively (BPS, 2024). This growing number shows activities to meet the market demand and potentially increases the risk of environmental impacts.

CPO production has adverse environmental impacts, particularly from the treatment of Palm Oil Mill Effluent (POME). The anaerobic degradation of organic matter in an open pond leads to the formation and release of methane (CH_4) into the atmosphere. Methane is a potent greenhouse gas with a global warming potential significantly higher than that of carbon dioxide. In life cycle impact assessment, the CML-IA Baseline method characterizes methane with a factor of 28 kg CO_2-equivalent per kg CH_4 over a 100-year time horizon (GWP100), indicating its higher contribution to climate change compared to CO_2. Consequently, methane emissions from open ponds constitute a significant contributor to global climate change (IPCC, 2021), highlighting the need for targeted mitigation and environmental strategies.

Recent studies have reported that methane emissions from POME treatment contribute significantly to the overall greenhouse gas emissions in palm oil production, emphasizing the environmental relevance of mitigation efforts in Indonesia and globally. POME treatment represents a key hotspot in the carbon footprint of palm oil production, primarily due to the high organic content of wastewater that drives anaerobic degradation and greenhouse gas emissions under conventional open pond conditions (Manikandan et al., 2026). Open pond systems are identified as major sources of methane emissions, with certain ponds acting as high-emission hotspots within the treatment system (Onodera et al., 2023). In Indonesia, the palm oil industry is widely acknowledged as a major contributor to global greenhouse gas emissions. Enhancing POME management practices, including methane capture, is regarded as a crucial strategy for reducing emissions within the production system (PASPI, 2025).

However, previous studies have primarily focused on assessing the overall environmental impacts of palm oil mill operations, with limited attention to the quantitative evaluation of mitigation strategies. In particular, scenario-based assessments of methane capture implementation in POME treatment systems, including the quantification of environmental impact reductions under varying capture efficiencies, remain insufficiently explored. The implementation of methane capture in POME treatment represents an effective approach for mitigating methane emissions, with reported reduction efficiencies of up to 70–90% (Lim et al., 2021). This technology operates by capturing methane through closed anaerobic reactors or covered pond systems, which act as physical barriers that prevent methane emission into the atmosphere. The captured gas is subsequently conveyed to a collection system for purification and storage, with potential for utilization as a renewable energy source. However, this study primarily analyzes methane emission reduction, showing that methane capture technology can effectively mitigate methane emissions from POME treatment.

A comprehensive evaluation of the environmental impacts under both conventional open-pond and methane capture scenarios is essential to quantify their respective contributions. The Life Cycle Assessment (LCA) provides a systematic framework for evaluating environmental impacts across the entire process life cycle. Such analysis is critical for establishing a scientific basis to support informed decision-making and the development of effective mitigation strategies in the palm oil industry. Therefore, this study aims to evaluate the environmental impact reduction potential of methane capture implementation in POME treatment using an LCA approach by comparing conventional open-pond and methane capture scenarios.

2. Method

This study was conducted at an operational palm oil processing facility in Indonesia, where CPO is produced as the primary product. The study involved the collection and analysis of production data reflecting normal operating conditions, commonly referred to as a business-as-usual scenario. Environmental impact assessment and analysis were carried out using the LCA methodology in accordance with the principles and framework outlined in SNI ISO 14040:2016 and SNI ISO 14044:2017.

2.1. Life Cycle Assessment of CPO Production

The system boundaries of this study were defined using a gate-to-gate approach, focusing on processes within the palm oil mill. The system encompasses the conversion of fresh fruit bunches (FFB) into CPO as the primary product, including supporting utility operations such as the water treatment plant, power generation unit, and wastewater treatment plant (Figure 1). Processes occurring outside the mill boundaries, such as plantation activities and final products distribution, were excluded from the analysis. The gate-to-gate approach ensures alignment with the study objective and enables a focused assessment of methane emissions and mitigation in POME treatment. Emissions associated with energy, fuel, and chemical inputs were accounted for through background data in the LCA model, ensuring that their contributions are reflected in the life cycle inventory.

This study refers to the Product Category Rules (PCR) for Basic Chemicals (UN CPC 341, 342, and 345, excluding subclass 3451), Version 1.1.5 (2021), as the LCA framework to ensure a systematic assessment aligned with the defined goal and scope. All impact calculations were performed based on a declared unit of 1 kg of CPO produced. The selection of this declared unit follows PCR guidance, enabling consistent environmental impact comparisons and improving comparability with similar product-based LCA studies in the palm oil industry.

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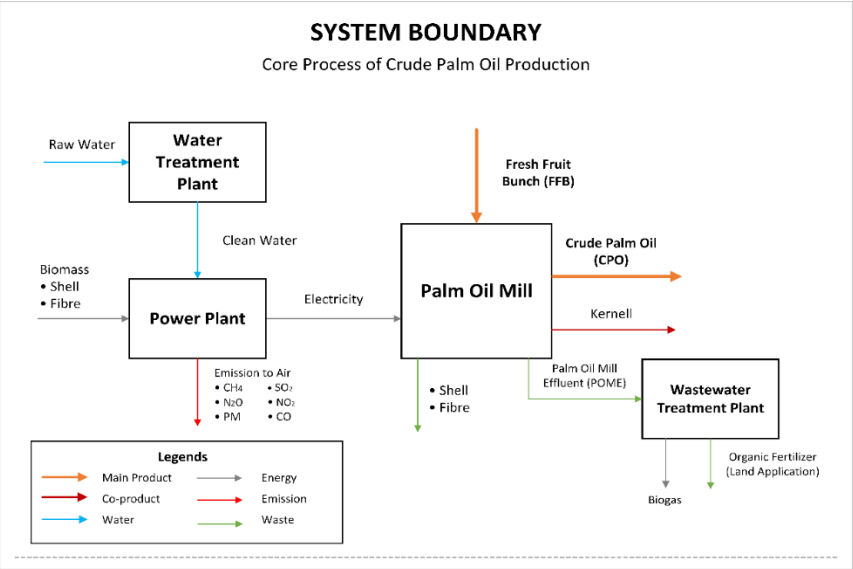


Figure 1. System Boundary of CPO Production

Table 1. Inventory Gate-to-Gate (Core Process) CPO Production

Core Process			
Input			
Category	**Inventory data**	**Amount**	**Unit**
Raw Material	Fresh Fruit Bunch	4.35E+00	kg
Other Material	Raw Water	3.48E+00	kg
Energy for Power Plant	Fuel - Solar	1.33E-03	kg
	Shell	2.24E-01	kg
	Fiber	4.55E-01	kg
	Steam	2.27E+00	kg
Energy for Process	Electricity	9.50E-02	kWh
Output			
Category	**Inventory data**	**Amount**	**Unit**
Product	CPO	1.00E+00	kg
Co-product	Kernell	1.93E-01	kg
Waste	POME	2.69E+00	kg
	Shell for Power Plant	2.24E-01	kg
	Fiber for Power Plant	4.55E-01	kg
Emission	CO_2	3.75E-03	kg
	CH_4	9.50E-02	kg
	N_2O	4.75E-02	kg
	NO_2	2.67E-04	kg
	CO	5.61E-04	kg
	Particulate	1.30E-04	kg
	SO_2	5.90E-05	kg

LCI consists of the identification, collection, and quantification of all input and output flows associated with the analyzed system (Lim et al., 2023). Inputs encompass material and energy consumption, whereas outputs include primary product, co-product, and emissions to the environment. In this study, inputs were obtained from the company's operational records covering the 2024–2025 period. The dataset comprised primary data collected through field surveys, interviews, laboratory analyses, and emission calculations, as well as secondary data sourced from the Ecoinvent v3.11 database and relevant literature to support the analysis.

LCIA aims to evaluate potential environmental impacts based on inventory data modeled in the LCI stage. In this study, data analysis was conducted using openLCA version 2.5.0, Ecoinvent database v3.11, and the Cut-off LCI system model. The environmental impact assessment focused on impact categories directly related to the implementation of methane capture, such as Global Warming Potential (GWP) and Photochemical Ozone Formation Potential (POFP). These impact categories were selected based on the study objective, which is to evaluate methane emission mitigation from POME treatment. Methane is a key contributor to climate change due to its high global warming potential and also acts as a precursor in tropospheric ozone formation, thereby influencing POFP (Reijnders, 2025). Impact calculations were conducted using the CML-IA Baseline method, which provides a standardized framework for impact classification and characterization, allowing comprehensive assessment and comparability across studies (Krisi et al., 2022).

2.2. Methane Capture Scenarios for Environmental Improvement

Under existing POME treatment, open pond systems are commonly used for POME treatment, enabling the anaerobic degradation of organic matter (Suharyo et al., 2019; Al-Amshawee et al., 2020). This process generates methane emissions, that contributing to GWP (Mohammad et al., 2021; Putro, 2022). As an environmental improvement strategy, a methane capture scenario was developed to recover methane generated during POME treatment. This study focuses on evaluating methane emission reductions from the implementation of methane capture.

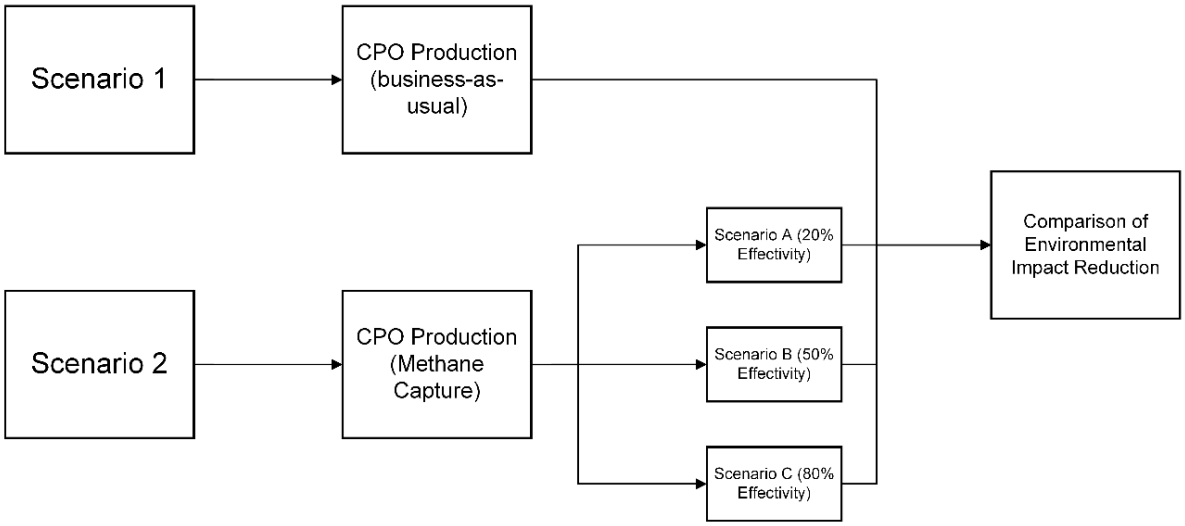


Figure 2. Design Scenario

Methane capture scenarios were modeled at the LCI stage by adjusting the methane emission output for each implementation scenario (Figure 2). The inventory was developed based on calculations of the proportion of methane successfully captured and the remaining methane released into the environment under each methane capture scenario. Subsequently, the inventory results for each scenario were evaluated at the LCIA stage. The methane capture scenario comprised three scenarios representing different levels of capture efficiency, 20% (Scenario A), 50% (Scenario B), and 80% (Scenario C), reflecting varying technological performance levels and implementation conditions of methane capture.

Scenario A represents the initial stage of methane capture implementation, characterized by relatively low system performance due to system design and operational limitations typically encountered during early deployment. Scenario B reflects improved system performance under intermediate operational conditions, which are commonly observed in conventional methane capture implementations. In contrast, Scenario C represents high-performance operating conditions achieved through optimized technology design and effective operational management.

Variations in capture efficiency were applied to develop scenario-specific inventories for quantifying differences in methane emissions. Methane emissions were estimated using a process-based approach derived from biogas

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generation, calculated by multiplying the mass of POME processed by the biogas production factor. The estimation depends on key parameters, including the biogas production factor, methane content in biogas, and conversion to mass units using methane density under standard conditions. Variability in these parameters, as well as in capture efficiency, may introduce uncertainty in the emission estimates.

The methane content of the biogas was assumed to be 55% of the total biogas volume and subsequently converted into mass units using a methane density of 0.656 kg/m^3 under normal temperature and pressure conditions (Sarwani et al., 2019). Methane emissions released to the environment under each methane capture scenario were determined as the residual emissions after accounting the amount of methane captured based on the assumed capture efficiency. The inventory results for each scenario were analyzed using the same LCA framework applied to the business-as-usual conditions to ensure consistency in impact assessment. The resulting environmental impacts were compared with the business-as-usual condition to evaluate the potential reductions achieved through methane capture implementation in the palm oil industry.

$$Biogas_{prod}\ (m^3) = POME\ (kg)\ x\ f_{biogas} \quad (1)$$

$$CH_4^{vol}\ (m^3) = Biogas_{prod}\ x\ 0{,}55 \quad (2)$$

$$CH_4^{mass}\ (kg) = CH_4^{vol}\ x\ \rho CH_4 \quad (3)$$

$$CH_4^{released}\ (kg) = CH_4^{mass}\ x\ (1 - \eta\text{MC}) \quad (4)$$

with:

$$f_{biogas} = 28\frac{m^3}{ton}POME$$

$$\rho CH_4 = 0{,}656\ kg/m^3$$

$$\eta\text{MC} = methane\ capture \text{ effectivity}$$

3. Result and Discussion

3.1. Environmental Impacts of CPO Production under Business-as-Usual Condition

The GWP and POFP values of CPO production under business-as-usual conditions are presented in Table 2. Based on the normalized results, the GWP value is more than 1.5 times higher than that of POFP. This finding indicates that POME treatment using open pond systems under business-as-usual conditions contributes to climate change, primarily due to anaerobic degradation processes that result in the release of methane emissions (Judijanto, 2025). In addition, methane emissions act as a precursor in photochemical oxidant formation (Ivensen & Roslev, 2025), which is reflected in the POFP impact category, although its contribution is relatively lower compared to GWP.

The GWP values obtained in this study fall within a range comparable to those reported in previous LCA studies of the palm oil industry. Schmidt and Rosa (2020) reported average GWP values of 3.41 kg CO_2-eq per kg of Refined Bleached and Deodorized (RBD) palm oil produced at RSPO-certified processing facilities and 5.34 kg CO_2-eq per kg at non-RSPO-certified facilities. Although differences exist in product type and processing characteristics, these values indicate a comparable magnitude of environmental impact to the LCIA results for CPO production in this study. Similarly, the POFP value derived in this study is consistent with trends reported in earlier research. Kristina et al. (2025) reported an average POFP value of 2.18 × 10^{-2} kg C_2H_4-eq associated with CPO production activities. Variations in POFP values between studies can be correlated with differences in system boundaries, geographical locations, product coverage, and processing technologies considered in the respective analyses.

Table 2. Environmental Impact Results of CPO Production

No	Impact Category	Impact (impact/kg CPO)	Reference Unit	Impact Calculation Method

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1	Global Warming Potential (GWP)	2.56E+00	kg CO_2 eq	CML IA Baseline
2	Photochemical Oxidant Formation Potential (POFP)	1.75E-03	kg C_2H_4-eq	CML IA Baseline

Methane (CH_4) is a major contributor to both environmental impact categories assessed in this study. As a greenhouse gas, methane has a substantially higher heat-trapping capacity than carbon dioxide, leading to greater retention of heat in the atmosphere and a subsequent increase in global temperatures. Consequently, methane emissions contribute significantly to GWP (Thakur & Solank, 2021). In addition, in climate change, methane also contributes to POFP through atmospheric reactions with nitrogen oxides (NO_x) in the presence of solar radiation, leading to the formation of tropospheric ozone (O_3) (Mar et al., 2022). Contribution analysis indicates that NOx constitutes the principal precursor to POFP, predominantly arising from biomass combustion in boilers during mill operations. Methane is identified as the second-largest contributor, primarily originating from POME treatment processes. Although not the primary precursor, methane plays a significant role in POFP formation through its interactions with NO_x under sunlight exposure. Unlike stratospheric ozone, which provides protective benefits, tropospheric ozone is a harmful air pollutant that adversely affects human health, including respiratory, cardiovascular, and neurological systems (Donzelli & Suarez-Varela, 2024). Furthermore, tropospheric ozone acts as a secondary greenhouse gas, thereby exacerbating global warming (Liu et al., 2022).

3.2. Environmental Performance of Methane Capture Scenarios

This study further evaluates the implementation of methane capture as an environmental improvement strategy by comparing scenarios A, B, and C to business-as-usual conditions (Table 3). All three scenarios showed a reduction in both environmental impact categories, demonstrating that methane capture effectively lowers impacts. Additionally, there is a clear link between the efficiency of methane capture and improved environmental performance. The reduction in GWP is primarily due to more controlled POME treatment using a closed system, which limits methane emissions into the atmosphere (Pallikodathan et al., 2025). While the POFP category also decreased, the reduction was relatively smaller. Since methane is a precursor for photochemical oxidation reactions, its reduction leads to decreased formation of photochemical oxidants (Archibald et al., 2020; Tasumi, 2023).

Table 3. Comparative Environmental Impact Assessment of *Methane capture* Scenarios with Varying Capture Efficiencies

Impact Category	Reference Unit	Environmental Impact Result				Percent Impact Reduction		
		Current Condition	*Methane capture* 20%	*Methane capture* 50%	*Methane capture* 80%	*Methane capture* 20%	*Methane capture* 50%	*Methane capture* 80%
Global Warming Potential (GWP)	kg CO_2 eq	2.56E+00	2.41E+00	2.18E+00	1.88E+00	**5.93%**	**14.83%**	**26.70%**
Photochemical Oxidant Formation Potential (POFP)	kg C_2H_4-eq	1.75E-03	1.71E-03	1.66E-03	1.60E-03	**1.87%**	**4.67%**	**8.40%**

The results of this study align with previous LCA findings on POME treatment. Alfiridho et al. (2023) reported that the implementation of methane capture was able to reduce the GWP, respiratory organics impact, and aquatic eutrophication by 76.24%, 91.20%, and 99.47% per ton CPO produced. Similar findings were also reported by Rahman et al. (2024), who evaluated the effectiveness of methane capture in CPO production and showed that increasing effectiveness from 84% to 86% and up to 88% resulted in GWP reduction by 1.5% and 3.1%, respectively. These results indicate that methane capture performance is strongly influenced by the level of operational effectiveness, which aligns with this study's approach in evaluating several levels of methane capture scenarios.

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Although methane was identified as the dominant contributor to GWP, the overall reduction under the 80% capture efficiency scenario reached only 26.70%. This outcome reflects the fact that methane capture primarily reduces emissions from POME treatment, while other emission sources within the system boundary, such as biomass combustion and energy-related inputs, remain unaffected. Consequently, the overall reduction in GWP is limited by the continued contribution of these non-methane emission sources.

Methane capture, as supported by LCA-based simulations, has proven effective in industrial applications. For example, in the palm oil industry, LCA studies report a reduction of 2.3–3.5 tons CO_2-eq per ton of FFB processed when captured biogas is used for power generation, confirming both operational and environmental advantages (Judianto, 2025). Similarly, in the mining sector, methane capture shows significant emission mitigation potential, reinforcing its effectiveness as a cross-sector strategy for environmental impact reduction (Borowski et al., 2025). Beyond emission reduction, captured methane offers potential for further utilization within a broader carbon management framework. Carbon Capture and Utilization (CCU) represents a relevant perspective, focusing on converting captured carbon-based gases into value-added products or energy. LCA studies on CCU technologies indicate that utilizing carbon-based gases, including methane, can significantly reduce carbon footprints, particularly when integrated with energy systems (Gracia-Garcia et al., 2020). While methane capture in this study is not modeled as a CCU system, it represents a potential pathway toward more advanced carbon utilization strategies.

4. Conclusion

This study provides an evaluation of environmental impact reduction using an LCA framework on the potential implementation of methane capture in POME's open ponds in the palm oil industry. The results demonstrate that increasing methane capture efficiency leads to a progressive reduction in GWP and POFP, reflecting the direct link between methane emission control and the mitigation of climate change and human health impacts. Hence, LCA findings provide valuable insights into the environmental benefits of methane capture and serve as a fundamental basis for decision-making in the development of environmental improvement strategies.

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