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Effectivity of Methane Capture in Crude Palm Oil Production at Mill J, PT XYZ, Sumatera Island: A Life-cycle Assessment

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ABSTRACT

Indonesia's crude palm oil sector has become the most significant agricultural sector. However, if the business does not sufficiently regulate its emissions and discharge, the rise of the CPO industry may also have detrimental effects on the environment. Life-cycle assessment, or LCA, is one technique for assessing the environmental impact of CPO-producing processes. Using openLCA v.2, this study evaluates the possible ecological effects of Sumatera Island's Mill J, PT XYZ, CPO manufacturing system. According to this analysis, in 2022, the mill and plantation processes contributed to environmental impacts. The impact assessment's results, including the potential for global warming, is 8.74E-01 kg CO_2eq/kg CPO, ozone layer depletion is 6.32E-08 kg CFC-11 eq/kg CPO, and acidification is 2.5E-03 kg. A methane capture scenario was analyzed, increasing the efficiency from 84% to 86% and 88%. The results showed that all impacts decreased with increased methane capture efficiency, reducing the global warming potential by 1.4% to 3.5%. These findings confirm the potential feasibility of increased methane capture efficiency in the palm oil industry to achieve sustainable improvement and targets.

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1. Introduction

Countries in Southeast Asia have become the dominant forces in the production of crude palm oil (CPO) globally. With tropical climates, Indonesia and Malaysia leverage these conditions to become leading producers of CPO. In 2015, oil palm plantations covered around 9 million hectares of land in Indonesia and generated 32.5 million tons of CPO and its derivatives. This significant output has a considerable impact on regional and global economies. From an economic perspective, CPO production holds substantial value. The export value of CPO and its derivatives from Indonesia reached about USD 17 billion in 2015, making CPO one of the primary export commodities for the producing countries [27]. The versatility of CPO extends beyond traditional use, finding applications in producing food [30], cosmetics [3], biofuels [4], biodiesel [7], and various other commodities [33].

However, the increase in palm oil plantations in tropical regions has raised concerns about its environmental impact on tropical rainforests. The competition between palm oil cultivation and preserving these vital ecosystems underscores the need to assess the ecosystem consequences [28].

Palm oil production involves both the palm oil mill and the plantation, realizing wastewater and solid waste pose environmental risks if not managed properly.

Life-cycle assessment (LCA) emerges as a valuable tool to gauge the ecological footprint of CPO production considering components such as the nursery, palm oil mills, waste treatment plants [8], boilers, and water treatment plants [15], [16], [17]. The environmental effects of CPO production cover various issues, including carcinogenic and respiratory impacts, global warming, radiation, ecotoxicity, acidification/eutrophication, land-use changes, consumption of minerals, ozone layer depletion, and fossil fuel consumption. The extent of these effects varies based on the manufacturing techniques employed throughout the production system [18]. Globally, numerous studies have investigated the LCA of CPO, revealing diverse outcomes influenced by factors such as location, manufacturing system, goals, and scope. Notably, climate change is a significant concern associated with CPO production in Indonesia. openLCA software assessments indicate that CPO-based biomass carries a 66% higher environmental impact than Jatropha-based CPO [14], [15]. The reason for this is that Jatropha is capable of being cultivated in infertile land and possesses the ability to withstand drought, resulting in less water consumption.

Focusing on the ground, PT XYZ operates palm oil mills on Sumatera Island, with Mill J gaining recognition for its advancements in composting. While solid waste processing has made strides, there is a recognition that further development is necessary. Methane capture practices emerge as a potential solution to enhance the production system's efficiency and mitigate its negative environmental impacts. Methane capture has the potential to decrease 45% of emissions originating from palm oil mill wastewater [29]. Thus, this study’s primary goal is to assess the impact of methane capture to reduce the environmental effects of Mill J's CPO manufacturing system, utilizing the reliable openLCA software for a comprehensive life-cycle assessment. This evaluation aims to provide insights into areas of improvement and contribute to the methane capture of the palm oil industry in the sector.

2. Research Methodology

2.1. General Description of CPO

The palm plantation and palm oil mill were the sites of the activity in Mill J. The estate spans roughly 23.17 hectares. Harvesting, insect control, land application (derived from palm oil mill effluent), fertilizer, and herbicides are all part of this estate's operations. Fresh fruit bunches (FFB) are processed into CPO in the palm oil mill. The boiler, methane capture, wastewater pond, and water treatment plant (WTP) are the other supporting systems for this process. This CPO manufacturing method produces kernels and biogas as a byproduct.

2.2. Goal and Scope

The environmental effects of the Mill J CPO production system have been evaluated using the cradle-to-gate paradigm in this life cycle assessment (LCA) study. This research refers to PCR (Product Category Rules) Basic Chemicals, UN CPC 341, 342, 345 (Except Subclass 3451) 2022 version 1.1.1 as an LCA framework to make sure that the study is focused, clear, and in line with its goals by clearly defining its purpose and scope. Fig. 1. shows the scope of this research. This system has two stages: the upstream and the core processes. The procedure that is not directly tied to the system is called the background stage. The product's environmental effects will depend on the energy and material inputs. The process immediately connected to the production system is what is happening in the foreground stage. This included all stages of the procedure, from the oil palm plantation (where FFB represents the output) to the transportation of the finished product to the storage facility. This study covers the kernel and biogas, which are byproducts of this system.

2.3. Procedures

Data from estates and mills are combined with firsthand observations in the field to compile inventory information. POME, EFB, shell, and fiber are additional outputs from the production process in addition to the main product (CPO). Once in the wastewater pond, the produced POME will either be applied to the land as a liquid fertilizer or flow to the plantation area. The boiler in the facility uses fiber and shell as fuel to make steam. The annual production of CPO is roughly 134.794.850 kg. Data on the fuels and chemical agents utilized in the system have been gathered and are shown in Table 1. The production capacity of the palm oil mill is 90 tons/hour. The process takes various inputs ranging from materials, energy, transport, etc. All of these data were inputted into openLCA software.

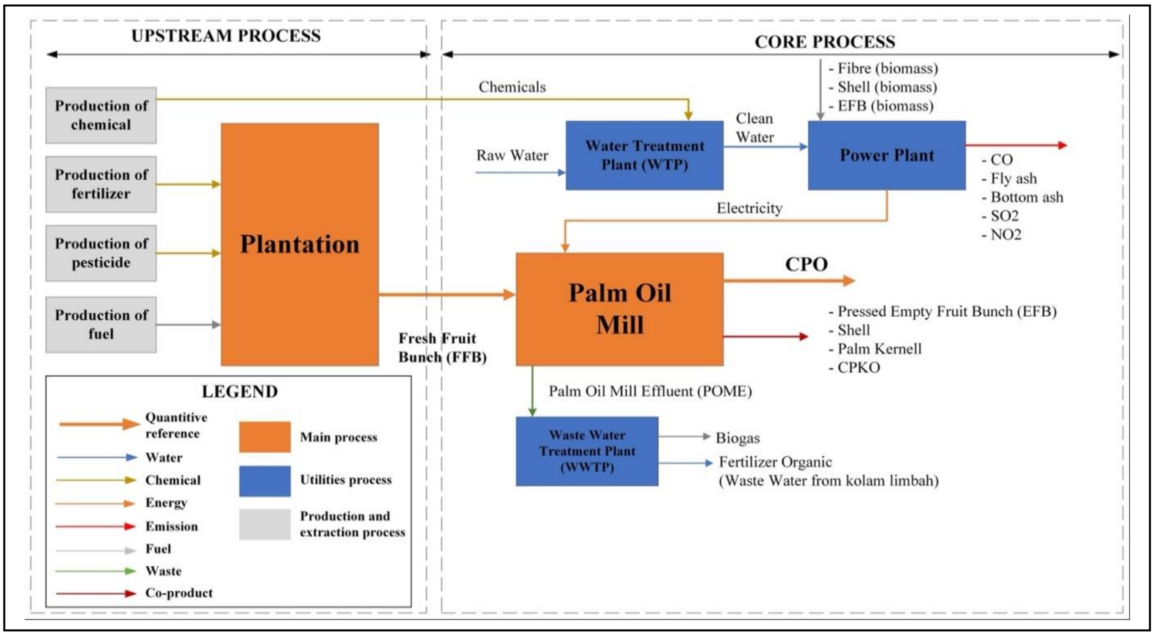

Fig. 1. System Boundary of CPO Production System at Mill J

Table 1. List of the input and output data for plantation and Mill with physical allocation

Input of Upstream			Output of Upstream		
	Quantity	***Unit***		***Quantity***	***Unit***
Energy			**Material**		
Fuel	5.73E-02	kg	Fresh Fruit bunch	1.00E+00	kg
Fertilizer					
NPK	2.10E-02	kg			
Urea	4.91E-04	kg			
Potassium chloride	3.66E-04	kg			
	1.16E-05	kg			
Input of Core			**Output of Core**		
	Quantity	***Unit***		***Quantity***	***Unit***
Energy			**Product**		
Electricity	8.73E-02	kWh	CPO	1	kg
Fuel	1.59E-04	kg	Shell	1.50E+00	kg
			Fibre	9.91E-01	kg
Material			Kernel	2.50E-01	kg
Steam	2.74E-03	kg	POME	2.24E+00	kg
Raw water	4.95E+00	kg	**Emission**		
Fresh Fruit Bunch	5.41E-03	kg	CO_2	1.88E-04	kg
			CH_4	3.13E-02	kg
			N_2O	3.26E-11	kg
			SO_2	4.01E-05	kg
			NO_2	5.33E-05	kg
			Particulate	2.49E-05	kg

2.4. Procedures

The purpose of the functional unit is to be used as a reference for input and output. Based on the PCR, the product system in this study is processing palm oil into a final product in the form of Crude Palm Oil with a declaration unit of 1 kilogram of the product, which covers 100% of the total Crude Palm Oil (CPO) product produced.

2.5. Procedures

Life cycle impact assessment (LCIA) is a step in evaluating the results of life cycle inventory analysis (LCI). At this stage, the data obtained from the LCI stage is processed and assessed for its impact on the environment. The inventory data is linked to specific environmental effects to measure each stage's contribution in the product life cycle to those ecological impacts [22]. The inventory analysis stage includes data collection and determination of relevant inputs and outputs of the product system [23]. This study used openLCA software and the CML-IA Baseline characterization method to determine impact indicators. Previous studies have used the CML-IA Baseline to evaluate various environmental impact categories in LCA [12]. The impact categories analyzed include Global Warming Potential (GWP), Acidification Potential, and Ozone Depletion Potential (ODP) [14].

2.6. Procedures

These include the company and the LCA study developers that made the assumptions in this investigation. The following are the study's presumptions:

a. The electricity consumption used to operate the CPO processing in the core process stage as a whole enters through the sterilization station. This is assumed because there is no specific breakdown of electricity consumption for each unit process within the core process.

b. The consumption of pesticides and fertilizers in the upstream process stage, especially in the outer plantations, is calculated based on the assumption of the ratio of pesticide and fertilizer usage in the core plantation. This is done to simplify the impact estimation of the use of agricultural chemicals in the outer plantations, considering the limitations of specific data at the unit process level.

c. Emission data calculations produced by Boiler N900 and Boiler N1300 include CO_2, while CH_4 emissions are calculated using a formulation based on the Heating Value of biomass fuel. This approach is chosen because the Heating Value provides a reliable estimate of the energy content of the biomass, which directly correlates with the potential CH_4 emissions during combustion.

2.7. Procedures

One of the most contentious methodological choices in LCA has proven to be the allocation procedure, mainly because it has a significant impact on study outcomes [19]. In this research, the products generated by Mill J consist of several different product components. In this regard, allocation can be avoided by using an allocation method for shared unit processes, employing a physical relationship approach based on the physical properties of these products, such as their mass (kg). Table 2 shows the allocation of products for this research.

Table 2. Plantation and mill data for input (1 kg CPO) with physical allocation

Product	**Allocation of Product**		
	CPO (product)	***Kernel (co-product)***	***Methane for biogas (co-product)***
Percentage Product	78%	20%	2%
Value	134.794.850 kg	33.739.769 kg	3.561.938 kg

3. Results and Discussion

3.1. Impact Assessment

Considering this is the current situation, the analysis in this impact assessment section is concentrated on the base scenario analysis. The palm oil sector in Indonesia has experienced significant expansion and accounted for 18-22% of the nation's CO_2 emissions in 2020 due to the growth of plantations in Kalimantan [34]. Based on the data presented in Fig. 2., it is evident that the transportation of TBS raw materials and other chemicals to the core process unit, FFB production activity, as well as the production of chemicals used in CPO processing, are the primary contributors to Global Warming Potential (GWP) impact.

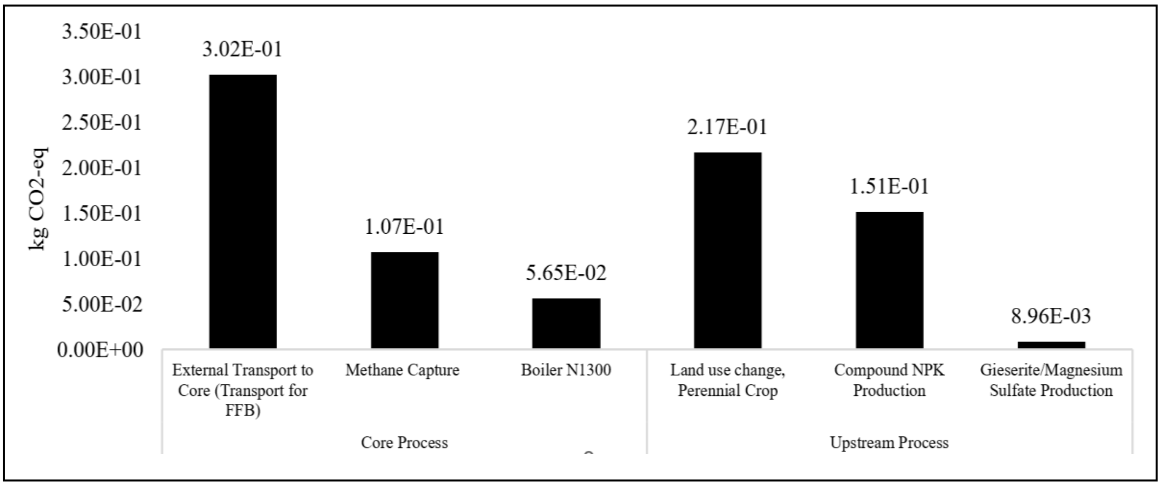

Fig. 2. Global Warming Potential of The Mill J

The GWP impact from CPO production is measured at 8.74E-01 kgCO_2eq/kg CPO. The upstream process stage is responsible for 46% of this impact, while the core process contributes 54%. The breakdown of the core process stage reveals that the transportation of TBS to the core process (External Transport to Core) using freight lorry 7.5-16 metric tons, Methane Capture, and Boiler N1300 are the most significant contributors to the GWP impact, each accounting for 3.02E-01 kgCO_2eq/kg CPO, 1.07E-01 kgCO_2eq/kg CPO, and 5.65E-02 kgCO_2eq/kg CPO, respectively. On the other hand, in the upstream process stage, the land use change process (Land use change, perennial crop), Compound NPK Production, and Gieserite Production are the most significant processes contributing to GWP, with each accounting for 2.17E-01 kgCO_2eq/kg CPO, 1.51E-01 kgCO_2eq/kg CPO, and 8.96E-03 kgCO_2eq/kg CPO, respectively. Furthermore, it is essential to note that the contributors to this GWP impact are Carbon dioxide (CO_2), Methane (CH_4), and nitrogen monoxide (N_2O).

The Potential Ozone Layer Depletion (ODP) value is based on the calculation of kg CFC-11 eq/Unit of product declaration using the CML-IA Baseline method [16], [20]. The ozone layer is a stratosphere that protects the Earth from direct exposure to ultraviolet (UV) radiation. Ozone layer depletion can potentially harm human health, animal health, terrestrial ecology, and water bodies. ODP allows various environmental adverse consequences, particularly affecting aquatic ecosystems, terrestrial ecosystems, and climatic interactions [31]. Moreover, ODP substantially affects human health, mainly through increasing exposure to ultraviolet B (UVB) radiation [32].

Fig. 2, which illustrates the potential ODP impact based on Pareto rules, shows that the transportation of raw materials and chemicals to the core processing unit, along with the production of these chemicals for CPO processing, are the main contributors to the dominant ODP impact, accounting for over 80% of the total impact. The ODP impact from CPO production is 6.32E-08 kg CFC-11 eq/kg CPO, with the upstream process stage contributing 18% and the core process stage contributing 82%. Referring to Figure 6.4, which illustrates the ODP contribution from each life cycle stage, it is evident that in the core process stage, the processes of transporting TBS to the core process (External Transport to Core) using freight lorries of 7.5-16 metric tons, the transportation of chemicals used in the core process (Transport for Chemicals in Core), and the treatment of hazardous waste are the most significant contributors to ODP, accounting for 5.21E-08 CFC-11 eq/kg CPO, 5.35E-11 CFC-11 eq/kg CPO, and 4.15E-13 CFC-11 eq/kg CPO, respectively. Meanwhile, in the upstream process stage, NPK Production, Glyphosate Production, and Pesticide Production are the significant contributors to ODP, accounting for 6.94E-09 CFC-11 eq/kg CPO, 1.63E-09 CFC-11 eq/kg CPO, and 8.63E-10 CFC-11 eq/kg CPO, respectively. The main contributor to this Ozone Depletion Potential (ODP) impact is Methane (CH_4).

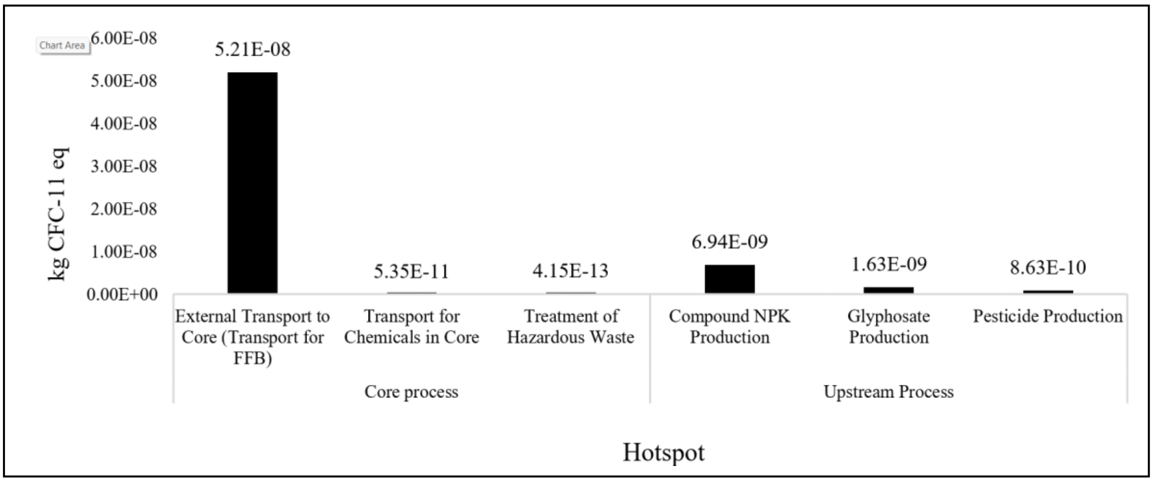

Fig. 3. Ozone Layer Depletion of the Mill J

Substances that can contribute to the formation of acid rain are known to have acidification potential. Acidification, caused by releasing sulfur dioxide and nitrogen oxides, lowers the pH levels in ecosystems. This leads to the washing out harmful metals that harm aquatic life and deplete soil nutrients. This phenomenon also indirectly impacts human health by polluting water and food sources and has a direct impact through respiratory problems caused by acidified air [26]. The total Acidification Potential (A.P.) impact from CPO production is 2.50E-03 kgSO_2eq/kg CPO. The life-cycle stages show that the upstream process contributes 38%, and the core process accounts for 62%. As illustrated in Fig. 3., which displays the contribution of A.P. impact from each life-cycle stage, it's evident that in the core process stage, the transportation of FFB to the core process (External Transport to Core) involving freight lorries of 7.5-16 metric tons, Boiler N1300, and the transportation of chemicals used in the core process (Transport for Chemicals in Core) are significant contributors to A.P., amounting to respectively 1.48E-03 kgSO_2eq/kg CPO, 4.95E-05 kgSO_2eq/kg CPO, and 1.80E-05 kgSO_2eq/kg CPO. Meanwhile, during the upstream process stage, the NPK Production process, land use change for perennial crops (Land Use Change, Perennial Crop), and Triple Superphosphate Production have the most significant impacts on A.P., with contributions of 6.64E-04 kgSO_2eq/kg CPO, 9.64E-05 kgSO_2eq/kg CPO, and 6.42E-05 kgSO_2eq/kg CPO, respectively. The main contributors to this Acidification Potential (A.P.) impact are nitrogen oxides (NO_x), sulfur dioxide (SO_x), and ammonia [21].

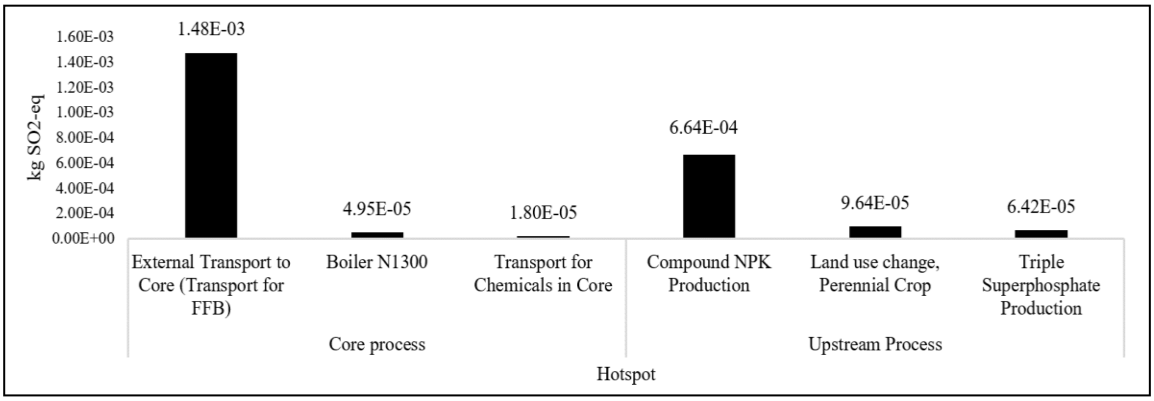

Fig. 4. Acidification Potential of the Mill J

3.2. Sensitivity Analysis

Sensitivity analysis seeks to ascertain the degree of significance of data that can be processed by adding or deleting input, output, and process units/subsystems [19]. Sensitivity analysis is an indispensable part of LCA, contributing to the robustness and credibility of the results by systematically addressing and quantifying uncertainties [24]. The effect of GWP is one of the major concerns in this study. A sensitivity analysis was carried out on methane capture subsystem expenditure. PT XYZ in the initial scenario. Based on the calculation results, the results of the total GWP impact from the initial scenario are 8.74E-01 kg CO_2 eq per 1 kg CPO or 1.180.802.886 per kg of CPO in 1 year with 84% efficiency for capturing methane. A previous study showed that methane capture efficiency decreases methane gas emissions by 77-78% [35]. A sensitivity analysis of the methane intake is also performed using the methane capture unit procedure. This study was conducted in the context of increasing methane usage. The emission into the air in the form of CH_4 is released into the environment with a capture efficiency of around 84% in this unit. However, approximately 16% of CH_4 is still escaping. Therefore, this sensitivity analysis is modeled based on the increase in the capture efficiency of CH_4 gas. Table 3. presents the inventory data used, providing information on the input and output values generated by the baseline methane capture unit and the assumption variations.

Table 3. Emission comparison of efficiency methane capture with CML-IA and Recipe Mid Point (H)

Indicator	Based Line		Scenario				Unit
			1[a]		*2[b]*		
	CML-IA	*Recipe Midpoint (H)*	*CML-IA*	*Recipe Midpoint (H)*	*CML-IA*	*Recipe Midpoint (H)*	
GWP	8.74E-01	9.20E-01	8.63E-01	9.07E-01	8.49E-01	8.88E-01	kg CO2-eq

[a.] Scenario 1: Efficiency methane capture 86%

[b.] *Scenario 2: Efficiency methane capture 88%*

Based on the sensitivity analysis results presented in Table 3, it is evident that the methane capture efficiency ranges from 86% to 88%; the results for efficiency capturing methane are 8.63E-01 kg CO_2 eq. The results for the combination of methane capture (88%) are 8.49E-01 kg CO_2 eq for a unit function of 1 kg of CPO. The different LCIA methods, CML-IA and Recipe Mid-Point (H) are shown in Fig. 5. The percentage of emission reduction in the CML-IA method in scenarios 1 and 2 is 1.5% and 3.1%, respectively. Meanwhile, the Recipe Mid-Point (H) method is 1.4% and 3.5%. The difference in the LCIA method between CML-IA and Recipe Mid-Point (H) is the different characterization factor values at CH_4. Sequentially, each value is 28 CO_2 eq/kg and 34 CO_2 eq/kg. Thus, increasing the efficiency of Methane Capture to reduce CH_4 emissions released into the air can be considered sensitive because it shows changes in the GWP impact value. These results indicate that improving the methane capture can reduce emissions of 114.440.827,65 kg CO_2 eq per kg of CPO in 1 year. Furthermore, methane capture can form biogas, which can be used as a renewable energy source. This biogas can generate electricity or heat for the mill, thereby reducing the use of fossil fuels.

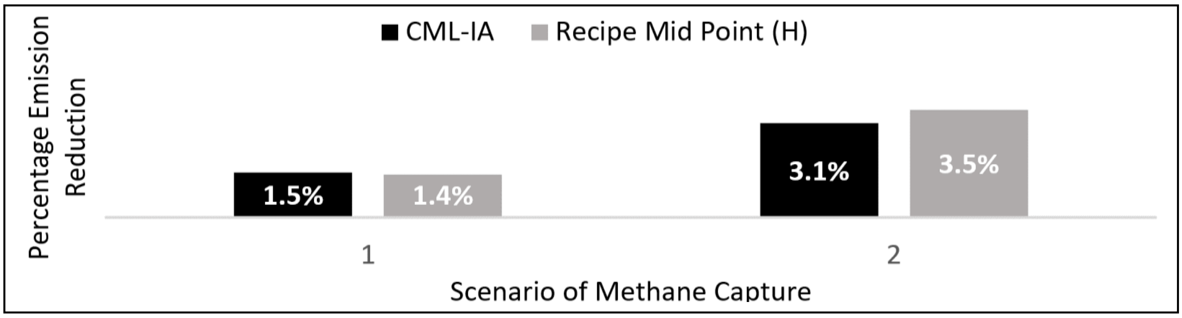

Fig. 5. Profile of emission reduction with scenario methane capture with different LCIA methods

3.3. Uncertainty Analysis

When assumptions, low-quality data, and data with significant uncertainty arise during computation, uncertainty analysis is performed [19]. This uncertainty analysis technique aims to investigate and determine how this uncertainty affects the dependability of LCIA results. Uncertainty analysis is essential in LCA studies because it addresses the variability and limitations inherent in data collection, modeling, and methodological choices, ensuring the reliability and wholeness of the results [25]. Examining this uncertainty can yield results by comparing the mean or mean value with the coefficient of variation or the standard deviation value.

Table 4. Uncertainty Analysis

Impact category	Unit	Coefficient of variance	Mean	Standard Deviation	Minimum	Maximum
GWP	kg CO2-eq	4.16%	1.28E+08	5.32E+06	1.12E+08	1.44E+08
ODP	kg CFC-11	6.49%	1.09E+01	7.08E-01	8.99E+00	1.30E+01
A.P.	kg SO2-eq	5.27%	3.86E+05	2.04E+04	3.32E+05	4.44E+05

Table 4 presents the results of the Monte Carlo analysis simulation, which indicate that all process units have well-distributed data, as the standard deviation value is lower than the mean value. The Monte Carlo analysis findings were derived from the LCIA results after 1000 iterations. Several limitations and assumptions can impact the interpretation of the results. The use of secondary data from the database, which has different temporal and geographical correlations, considerably affects the uncertainty analysis of the study.

4. Conclusion

This study assessed the impact of methane capture scenarios to reduce the environmental impact of the CPO manufacturing system at PT XYZ using openLCA software. The environmental impact analysis showed that CPO production results in a global warming potential of 8.74E-01 kg CO_2eq/kg CPO, ozone layer depletion potential of 6.32E-08 kg CFC-11 eq/kg CPO, and acidification potential of 2.50E-03 kg SO_2eq/kg CPO. Sensitivity analysis revealed that increasing methane capture efficiency to 86% and 88% can reduce global warming potential to 8.63E-01 kg CO_2eq/kg CPO and 8.49E-01 kg CO_2eq/kg CPO, respectively. These findings underscore the importance of optimizing methane capture technology to reduce greenhouse gas emissions and support sustainability principles. PT XYZ can use these results to enhance environmental performance by investing in sustainable practices that reduce global warming potential. This aligns with global sustainability goals and addresses broader challenges in the palm oil industry, such as deforestation, biodiversity loss, and community impacts. Regular environmental impact assessments will promote transparency, accountability, and a more sustainable palm oil industry. Recommendations for PT XYZ and other stakeholders include improving methane capture efficiency and implementing broader mitigation strategies to reduce environmental impacts comprehensively.

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References

[1] N. Syechalad, R. Masbar, and M. Nasir, “the Analysis of Factors Affecting Cpo Export Price of Indonesia,” *Eur. J. Account. Audit. Financ. Res.*, vol. 5, no. 7, pp. 17–29, 2017, [Online]. Available: www.eajournals.org.

[2] H. Ali, S. Karimi, R. Febriamansyah, and H. Ali, “Analysis of export performance and export competitiveness trade of crude palm oil [CPO] industry in Indonesia with RSPO in India and United States markets,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 497, no. 1, 2020, doi: 10.1088/1755-1315/497/1/012043.

[3] N. M. Huda, N. Imro’ah, and D. R. Darmawanti, “Forecasting The Production of Crude Palm Oil (CPO) in Indonesia 2022 using the Grey(1.1) Model,” *Tensor Pure Appl. Math. J.*, vol. 3, no. 1, pp. 1–10, 2022, doi: 10.30598/tensorvol3iss1pp1-10.

[4] J. C. Kurnia, S. V. Jangam, S. Akhtar, A. P. Sasmito, and A. S. Mujumdar, “Advances in biofuel production from oil palm and palm oil processing wastes: A review,” *Biofuel Res. J.*, vol. 3, no. 1, pp. 332–346, 2016, doi: 10.18331/BRJ2016.3.1.3.

[5] N. W. Ayer, P. H. Tyedmers, N. L. Pelletier, U. Sonesson, and A. Scholz, "Co-product allocation in life cycle assessments of seafood production systems: Review of problems and strategies," *Int. J. Life Cycle Assess.*, vol. 12, no. 7, pp. 480–487, 2007, doi: 10.1065/lca2006.11.284.

[6] S. Z. Y. Foong, V. Andiappan, R. R. Tan, D. C. Y. Foo, and D. K. S. Ng, "Hybrid approach for optimization and analysis of palm oil mill," *Processes*, vol. 7, no. 2, pp. 1–27, 2019, doi: 10.3390/pr7020100.

[7] P. Djatmika, P. Listiningrum, T. B. Sumarno, D. F. Mahira, and C. P. M. Sianipar, "Just Transition in Biofuel Development towards Low-Carbon Economy: Multi-Actor Perspectives on Policies and Practices in Indonesia," *Energies*, vol. 17, no. 1, p. 141, 2023, doi: 10.3390/en17010141.

[8] N. Omran, A. H. Sharaai, and A. H. Hashim, "Visualization of the sustainability level of crude palm oil production: A life cycle approach," *Sustain.*, vol. 13, no. 4, pp. 1–16, 2021, doi: 10.3390/su13041607.

[9] M. H. Mohammadi Ashnani, A. Johari, H. Hashim, and E. Hasani, "Life cycle assessment of palm oil biodiesel production in Malaysia," *Appl. Mech. Mater.*, vol. 465–466, no. January, pp. 1080–1086, 2014, doi: 10.4028/www.scientific.net/AMM.465-466.1080.

[10] H. Zulkifli, M. Halimah, K. W. Chan, Y. M. Choo, and W. Mohd Basri, "Life cycle assessment for oil palm fresh fruit bunch production from continued land use for oil palm planted on mineral soil (part 2)," *J. Oil Palm Res.*, vol. 22, no. DECEMBER, pp. 887–894, 2010.

[11] Ahmadi *et al.*, "Cradle to Gate Life Cycle Assessment of Palm Oil Industry," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1143, no. 1, p. 012044, 2021, doi: 10.1088/1757-899x/1143/1/012044.

[12] D. A. P. Sari, M. Nikmah, and N. A. Sasongko, "Life Cycle Assessment in the Production Process of Crude Palm Oil (Cpo) on Palm Oil Plantation and Mills," *Int. J. GEOMATE*, vol. 25, no. 111, pp. 177–184, 2023, doi: 10.21660/2023.111.s8616.

[13] R. Rinaldo, S. Suprihatin, and M. Yani, "Life cycle assessment produksi crude palm oil (CPO) (studi kasus: PT X Provinsi Bengkulu)," *Agrointek J. Teknol. Ind. Pertan.*, vol. 17, no. 3, pp. 651–659, 2023, doi: 10.21107/agrointek.v17i3.17131.

[14] A. K. Paminto, M. Karuniasa, and E. Frimawaty, "Potential environmental impact of biodiesel production from palm oil using LCA (Life Cycle Assessment) in Indonesia," *J. Pengelolaan Sumber. Alam dan Lingkung.*, vol. 12, no. 1, pp. 64–71, 2022, doi: 10.29244/jpsl.12.1.64-71.

[15] S. Yusoff and S. B. Hansen, "Feasibility study of performing a life cycle assessment on crude palm oil production in Malaysia," *Int. J. Life Cycle Assess.*, vol. 12, no. 1, pp. 50–58, 2007, doi: 10.1065/lca2005.08.226.

[16] V. Subramaniam, Z. Hashim, S. K. Loh, and A. A. Astimar, "Assessing water footprint for the oil palm supply chain- a cradle to gate study," *Agric. Water Manag.*, vol. 237, no. March, p. 106184, 2020, doi: 10.1016/j.agwat.2020.106184.

[17] E. S. M. Ibnu Alfaridho, Dwi Ermawati Rahayu, "Life Cycle Assessment (LCA) Analysis of Wastewater Treatment at Pahu Makmur Palm Oil Mill." Jurnal Teknologi Lingkungan, pp. 116–126, 2023, doi: e-ISSN 2548-6101 p-ISSN 1411-318X.

[18] Z. Hashim, V. Subramaniam, M. H. Harun, and N. Kamarudin, "Carbon footprint of oil palm planted on peat in Malaysia," *Int. J. Life Cycle Assess.*, vol. 23, no. 6, pp. 1201–1217, 2018, doi: 10.1007/s11367-017-1367-y.

[19] R. S. H. Malik and B. M. S., Muhammad Mufti Azis, "Life Cycle Assessment of Medical Solid Waste Management," *J. Ind. Eng. Educ.*, vol. 1, no. 1, pp. 83–96, 2023, [Online]. Available: http://scienceflora.org/journals/index.php/rrst/article/viewFile/1178/1163.

[20] V. Subramaniam, C. Y. May, H. Muhammad, Z. Hashim, Y. A. Tan, and P. C. Wei, "Life cycle assessment of the production of crude palm oil (part 3)," *J. Oil Palm Res.*, vol. 22, no. DECEMBER, pp. 895–903, 2010.

[21] D. A. P. Sari, A. Rahmah, and N. A. Sasongko, "Life Cycle Assessment (LCA) in Palm Oil Plantation and Mill with Impact Categories Global Warming Potential, Acidification, and Eutrophication," *Int. J. Membr. Sci. Technol.*, vol. 10, no. 2, pp. 797–807, 2023, doi: 10.15379/ijmst.v10i2.1236.

[22] Jayasundara, P. M., and Rathnayake, M. "Fruit and vegetable waste utilization and sustainability: chapter 10 - environmental impacts and sustainability assessment of fruit and vegetable waste valorization through life cycle assessment (includes an overview of life cycle assessment from laboratory scale to industrial implementations and social & economic sustainability)". Academic Press, 181-212. 2023.

[23] Lim, C.H., Bok, C.H., Ngan, S.L., How, B.S., Ng, W.P.Q., and Lam, H. L. "Evaluation of sustainable palm oil production certification via LCA". Reference Module in Earth Systems and Environmental Sciences, Elsevier. 2023.

[24] Martínez-Blanco, J., Lehmann, A., Chang, Y.-J., & Finkbeiner, M. "*Sensitivity analysis in life cycle assessment: A review of recent trends and recommendations"*. Environmental Science & Technology, 54(16), 10151-10167. 2020.

[25] Barahmand, Zahir and Eikeland, Marianne S. "*Life Cycle Assessment under Uncertainty: A Scoping Review"*. World 2022, 3, 692-717. 2022.

[26] Falkenberg, L.J.; Bellerby, R.G.J.; Connell, S.D.; Fleming, L.E.; Maycock, B.; Russell, B.D.; Sullivan, F.J.; Dupont, S. "*Ocean Acidification and Human Health"*. Int. J. Environ. Res. Public Health, 17, 4563. 2020.

[27] Warsito, Teguh. "*The economic determinant factors of Indonesia crude palm oil exports to India"*. Ekuivalensi Jurnal Ekonomi Bisnis, 6(2). 2020.

[28] Beyer, Robert M., Duran, America P., Rademacher, Tim T., Martin, Philip, Tayleur, Catherine, Brooks, Sharon E., Coomes, David, Donald, Paul F., and Sanderson, Fiona J. "*The environmental impacts of palm oil and its alternatives*". bioRxiv 2020.02.16.951301. 2020.

[29] IOI Corporation Berhad. "*Progressing Towards Net Zero*". 196901000607 (9027-W). 2022.

[30] Mba, Ogan I., Dumont, Marie-Jose´e, and Ngadi, Michael. "*Palm Oil: Processing, Characterization and Utilization in the Food Industry – A Review*". Food Bioscience 10(4). 2015.

[31] Pyle, J.A., Keeble, J., Abraham, N.L. et al. *Integrated ozone depletion as a metric for ozone recovery*. Nature 608, 719–723 (2022)

[32] Umar, Sheikh Ahmad. Tasduq, Sheikh Abdullah. *Ozone Layer Depletion and Emerging Public Health Concerns - An Update on Epidemiological Perspective of The Ambivalent Effects of Ultraviolet Radiation Exposure.* Frontiers on Oncology (12). 2022.

[33] Mairiza, L., Khadafi, M., Muhibbul, Budiman, I., and Yunardi, Y. "*An overview of potential production of bio-lubricant in Indonesia*". IOP Conf. Ser.: Earth Environ. Sci. 951 012061. 2022.

[34] Carlson, Kimberly M., Heilmayr, Robert., Gibbs, Holly K., et al. *Effect of oil palm sustainability certification on deforestation and fire in Indonesia* Proceedings of the National Academy of Sciences 115(1). 2018.

[35] Febijanto, Irhan. *"Potensi Penangkapan Gas Metana dan Pemanfaatannya Sebagai Bahan Bakar Pembangkit Listrik di PTPN VI Jambi."* Jurnal Ilmu Teknologi Lingkungan Vol. 1 (10). 2010.