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Research Paper

Improved Environmental Management Performance in the Crude Palm Oil (CPO) Production Process using a Life Cycle Assessment Approach

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Abstract

The palm oil production process at XYZ company, from the plantation subsystem, such as maintenance and harvesting, to processing in the mill, has the potential for significant environmental impacts, including greenhouse gas emissions from the use of diesel fuel. This study aims to evaluate the potential environmental impacts of producing one ton of Crude Palm Oil (CPO) at XYZ company using a Life Cycle Assessment (LCA) with a cradle-to-gate approach. The CML-IA Baseline method was employed, focusing on three main impact categories: Global Warming Potential (GWP 100a), Acidification Potential (AP), and Eutrophication Potential (EP). Primary data were collected directly from XYZ company through interviews, observations, and documentation, supported by relevant secondary data. Life Cycle Inventory (LCI) analysis quantified inputs such as fertilizers, diesel fuel, and electricity, as well as outputs in the form of liquid and solid waste. The Life Cycle Impact Assessment (LCIA) results indicate that factory processing operations are the primary contributors to environmental impacts. The GWP 100a impact value was identified as 2×10^4 kg CO_2 eq./ton CPO, the AP value as 18.5 kg SO_2 eq./ton CPO, and the EP value as 7.8 kg PO_4 eq./ton CPO, with the most significant contributions coming from diesel fuel consumption and electricity use in the loading ramp process. Improvement recommendations focus on optimizing the replacement of diesel fuel with biodiesel to minimize the impact.

Keywords

CPO, Cradle-to-Gate, Environmental Impact, LCA

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1. INTRODUCTION

The palm oil industry plays a vital role in the Indonesian economy. Indonesia is currently the largest crude palm oil (CPO) producing country in the world. Based on data from the 2021–2023 National Leading Plantation Statistics, Indonesia's oil palm area in 2023 reached 16,833,985 Ha, consisting of smallholder plantations of 6300,426 Ha, state plantations of 573,613 Ha, private plantations of 8429,329 Ha, and the area will be confirmed at 1530,617 Ha Indonesia produced >48.3 million tons of CPO in 2023. Palm oil production is mainly for export, making Indonesia the world's largest palm oil exporter. Indonesia's palm oil production centers are located in nine provinces, namely Riau province (18.71 %), Central Kalimantan (18.19 %), West Kalimantan (11.25 %), North Sumatra (10.68 %), East Kalimantan (8.97 %), South Sumatra (8.77 %), Jambi (5.39 %), West Sumatra (3.02 %), South Kalimantan (2.83 %), and other provinces (12.28 %) (Raynita et al., 2025).

However, despite its significant economic contribution, the palm oil industry also faces major challenges in maintaining environmental sustainability (Maisarah and Dian, 2024). Palm oil production significantly impacts Global Warming Potential (GWP) emissions and biodiversity (Schmidt and Weidema, 2026). Despite its economic benefits, the palm oil industry also generates a significant amount of waste. During the processing stage, large quantities of by-products such as palm kernel oil (PKO), palm kernel cake, pressed fiber, and palm oil mill effluent (POME) are produced. Although these residues are rich in organic matter, they have historically been underutilized, leading to environmental issues such as water pollution and GWP emissions (Dwi et al., 2025). Quantifying the impact of our production systems on the environment has become a milestone for agricultural commodity chains. Given the various pollution risks (eutrophication, global warming, ecotoxicity), but also mitigation opportunities to reduce global warming, for instance, it is crucial to have an understanding and adapted models and tools that allow for identifying best practices to reduce environmental impacts from agriculture (Bessou and Pardon, 2017).

XYZ company, a private company operating in South Solok Regency, West Sumatra, is one of the players in the palm oil industry in Indonesia that can produce 900 tons of Fresh Fruit Bunches (FFB) at a rate of 900 tons/day, producing 185.4 tons/day of CPO with an operating time of 20 hours. As a company involved in palm oil plantations and processing, XYZ has a responsibility to manage its operations sustainably and minimize adverse environmental impacts. South Solok Regency itself is an area with high biodiversity and is an important water catchment area for the surrounding region (Yanti et al., 2024).

This makes XYZ company an interesting case study because its operations can have a significant impact on the surrounding environment. Currently, XYZ Company does not have a comprehensive LCA study. LCA is a comprehensive and systematic methodology employed to evaluate the environmental impacts of a product, process, or activity over its entire life span, encompassing raw material extraction to ultimate disposal (Schinas et al., 2026). The absence of LCA-related research at XYZ company means that information on the magnitude of emissions, potential pollution, and opportunities for environmental improvement has not been systematically documented (Xu et al., 2026). Therefore, this research is important to enable the company to develop a scientific basis for formulating a more sustainable environmental management strategy while supporting compliance with international environmental regulations and standards. The environmental impact generated by XYZ company is increased carbon emissions from plantation and production processes, as well as forest fires during land clearing.

In identifying and analyzing the environmental impact of XYZ company activities comprehensively (Chaerul and Allia, 2019), a systematic and measurable approach is required (Harimurti et al., 2021). LCA is the appropriate method for this purpose. LCA makes it possible to trace the entire life cycle of a product, from the acquisition of raw materials to the processing of waste, so that the critical stages that produce the most tremendous environmental impact can be identified (Azmi et al., 2025). It has been extensively utilized to support strategic planning on environmental management, define policy agendas and targets, and provide evidence for monitoring environmental concerns (e.g., global warming, release of toxic compounds, eutrophication, resource depletion) of products and services in multiple industrial sectors (Klöpffer et al., 2023), as well as to inform consumers through ecolabels and guide them towards more sustainable consumption choices (Courtat et al., 2023).

Previous studies have shown that the palm oil industry has the potential for significant environmental impacts. Rinaldo et al. (2023) reported that the most significant emissions were generated by industrial processing activities, amounting to 559.9 kg CO2-eq/ton of CPO. Sari et al. (2023) found that the most significant environmental impact from CPO production comes from factories, with a global warming potential (GWP) of 2.16×107 kg CO_2-eq/kg CPO/year, which presents only a total annual figure without details of process hotspots. Hawari (2021) showed that the most considerable GWP impact in the palm oil agroindustry supply chain comes from the distribution process, which focuses more on operational aspects of the supply chain and FFB transportation patterns, without presenting quantitative values from the Life Cycle Impact Assessment (LCIA) per functional unit. What distinguishes this study from previous research is that the latter did not specify which stage had the most significant impact. In contrast, this study found that the most significant impact occurred at the loading ramp stage.

Although there have been previous LCA studies on the palm oil industry, there are still limitations in presenting detailed life cycle inventory (LCI) data. This is particularly true regarding diesel consumption in wheel loaders and electricity usage on loading ramps. Both aspects have the potential to significantly contribute to the Global Warming Potential (GWP). Therefore, this study focuses on analyzing the contribution of operational energy to the environmental impact of each CPO processing unit. This study is novel.

This study explicitly analyses the environmental impact of XYZ company operations in South Solok Regency using primary field data, including observations, documentation, and interviews. Therefore, LCA results from other locations cannot be directly generalized to XYZ company. This is important because operational and environmental conditions at each palm oil company differ, so the environmental impact will vary accordingly. XYZ company is also the largest company among the two other large companies in West Sumatra. XYZ company's advantage over other large companies is that it holds Roundtable on Sustainable Palm Oil (RSPO) and Indonesian Sustainable Palm Oil (ISPO) certifications, and it has a conservation area (MBI, 2021).

This study also uses a cradle-to-gate approach that covers all stages of CPO production, from oil palm cultivation (maintenance and harvesting) to factory processing (extraction, purification, and storage). Thus, this study can provide a more complete picture of the environmental impact of CPO production at XYZ company. The CML-IA Baseline method used allows quantification of environmental impacts across various categories, including GWP, air pollution, soil acidification, and eutrophication because it is most relevant to the emission characteristics of the CPO processing process, particularly those from fuel use, energy consumption, and the potential release of compounds that cause air and water pollution, after LCA analysis in Sima Pro, these three impacts were the largest. Therefore, only these three impact categories were selected. The data from this analysis can be used to compare process stages and identify those with the greatest environmental impact. The following adds the system boundaries from start to finish (cradle-to-gate), this boundary encompasses all direct and indirect inputs (Sun

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et al., 2025). Can be seen in Figure 1, meanwhile for LCI flow diagram can be seen in Figure 2.

Based on the LCA results, this study will formulate specific, actionable recommendations for XYZ company to improve its environmental performance. These recommendations may include strategies to reduce greenhouse gas emissions, improve energy and water efficiency, and better manage waste. By emphasizing these aspects, this study can help promote a more sustainable palm oil industry in Indonesia, particularly in South Solok Regency.

The results of this study are also expected to serve as a reference for further research on sustainable palm oil production in Indonesia. By emphasizing these aspects, this research can help promote a more sustainable palm oil industry in Indonesia, particularly in South Solok Regency. The results of this research are also expected to serve as a reference for further research and support the government's efforts to achieve sustainable development targets.

2. EXPERIMENTAL SECTION

This study analyzed the life cycle of CPO products at XYZ company using the LCA method is a standardized and widely recognized methodology based on ISO 14.040–14.044 for quantifying the environmental impacts of products and systems across their entire life cycle, from raw material extraction to disposal (Dwi et al., 2025). The life cycle analyzed covers the process from oil palm cultivation to the CPO production process at the factory. The functional unit used was 1 ton of CPO. The purpose of this study was to measure and evaluate the environmental impacts of the CPO production process, including greenhouse gas emissions, water pollution, and resource use. This environmental impact was measured and analyzed using the CML-IA Baseline method because, in case several methods are available for obligatory impact categories, a baseline indicator is selected, based on the principle of best available practice. These baseline indicators are category indicators at "mid-point level" (problem-oriented approach)" (PRé Consultants and Authors, 2020). This study will follow the LCA stages listed in SNI ISO 14040, 2016, namely determining the objectives and scope (defining the research objectives, system boundaries, and functional unit functional units); inventory analysis (collecting input and output data from the system under study); impact assessment (assessing the environmental impact of the inventory data collected); and interpretation (analyzing the results of the impact assessment and formulating conclusions and recommendations). The results of this study are expected to provide quantitative data on the environmental impact of CPO production at XYZ company, which can be used as a basis for future system improvements.

This study uses three categories of impact, namely global warming, acidification, and eutrophication. The selection of these three specific impact categories is strictly justified by the prominent environmental profile of the palm oil agroindustry. Global Warming Potential (GWP) is selected due to national and international carbon reduction mandates, while Acidification Potential (AP) and Eutrophication Potential (EP) are critically chosen to address the direct local ecological carrying capacity. This relates specifically to the heavy application of synthetic nitrogen-phosphorus fertilizers in the plantations and the high volumes of organic compounds processed within the gate operations, which are known to be the primary drivers of localized soil acidification and aquatic eutrophication. The system boundary used is Cradle to Gate, which covers the plantation stage, including maintenance, harvesting, and transportation, and the production stage, used to determine the environmental and production impacts of a product. The analysis was conducted using the LCA approach, incorporating inventory data on the cultivation and processing of palm oil in Sima Pro and Microsoft Excel. Based on the analysis, the environmental impacts and alternative improvements for each production activity will be generated. The following table of emission factors is added, as shown in Table 1.

3. RESULT AND DISCUSSION

3.1 General

This study analyzes the Crude Palm Oil (CPO) product cycle at XYZ company from plantation activities to CPO production. This study uses the LCA method to examine the environmental impact of the production process for 1 ton of CPO, adopting a cradle-to-gate approach and a functional unit of 1 ton of CPO. This study follows SNI ISO 14040:2016, which comprises four stages of LCA: defining the objectives and scope, inventory analysis, impact assessment, and interpretation. XYZ company produces 45 tons/hour of fresh fruit bunches (FFB) using the Sima Pro 9.5 Professional database (PRé Consultants and Authors, 2020). Therefore, for a 20-hours workday, it produces 900 tons/day of FFB, resulting in 185.4 tons/day of CPO. To produce 1 ton of CPO, 4.854 tons of FFB are required with an Oil Extraction Rate (OER) or oil extraction rate at Company XYZ of 20.60%.

3.2 Definition of Objectives and Scope

The definition of objectives and scope in LCA research includes:

1. Objectives, including:
   This study aims to:
   a) Identify the inputs and outputs of the CPO production process at XYZ Company using the cradle-to-gate approach.
   b) Calculate and analyze the environmental impact resulting from the production process of 1 ton of CPO at XYZ Company.
   c) Formulate recommendations to minimize the environmental impact of the CPO production process at XYZ Company, based on the LCA results.

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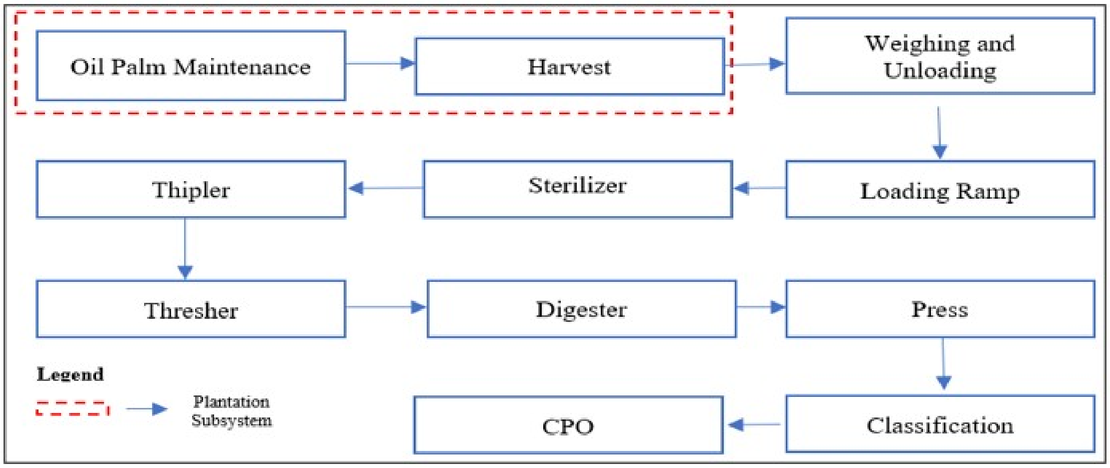

Figure 1. System Boundaries from Start to Finish (Cradle-to-Gate)

2. The scope includes:
   The scope of this study is:
   a) The research is being conducted at XYZ Company.
   b) The functional unit is 1 ton of CPO.
   c) The study uses the LCA method to comprehensively identify and assess the environmental impacts of the CPO product life cycle, following the ISO 14040 standard for conducting LCA.
   d) The system boundary in this study uses a cradle-to-gate approach that covers the palm oil cultivation process from maintenance to harvesting, as well as the CPO processing at the factory.
   e) The stages not examined in this study are nurseries and planting, as well as the stages to downstream factories and consumers. The exclusion of the nursery and land-clearing stages within this cradle-to-gate boundary is justified by the temporal allocation of the system. Since XYZ Company operates on well-established, mature, and productive oil palm stands (mature plantations), the environmental burdens associated with the short-term nursery phase and historical land-clearing activities are negligible when allocated over the entire 25-year productive lifespan of the palms, thereby focusing the functional assessment purely on active maintenance, harvesting, and milling utilities.
   f) Environmental impact assessment was conducted using the CML-IA Baseline method with 3 impact categories, namely: Acidification Potential (AP), Global Warming Potential (GWP 100), and Eutrophication Potential (EP);
   g) The inventory data in this study consists of data obtained directly from XYZ company (primary data) through interviews, field observations, and documentation studies, and secondary data obtained from company documents, scientific journal articles, and research reports.

3.3 Analysis Life Cycle Inventory (LCI)

Inventory analysis is the stage of collecting data, gathering it, and identifying it as input and output data (Heidari et al., 2022). Primary data was obtained directly from XYZ Company operations through field observations and recordings (Pogrzeba et al., 2026). This data was then verified against company operational documents and validated through confirmation with relevant parties to ensure the consistency and reliability of the inventory data used. The following is the inventory data from this study, divided into 2 tables: the Plantation Sub-system and the Milling Sub-system, as shown in Tables 2 and 3.

3.4 Life Cycle Impact Assessment (LCIA)

Environmental impact assessment using the CML IA Baseline method. In this method, the assessment stages include classification, characterization, and normalization. Characterization aims to estimate the magnitude of impact using inventory data in accordance with the relevant impact category. Normalization is used to assess a characteristic impact relative to other impact categories, so that an overview of each impact's significance level can be obtained.

3.4.1 Impact Classification and Characterization

Impact classification is the process of selecting relevant impact categories using the assessment method. In CPO production analysis, the impact categories examined include GWP, EP, and AP. The magnitudes of the impacts obtained can only be compared within the same category, as each category uses a different unit. The product network results for 1 ton of CPO are shown in Figure 3. The network results explain the process flow that affects the environment. The red lines indicate the processes with environmental impacts

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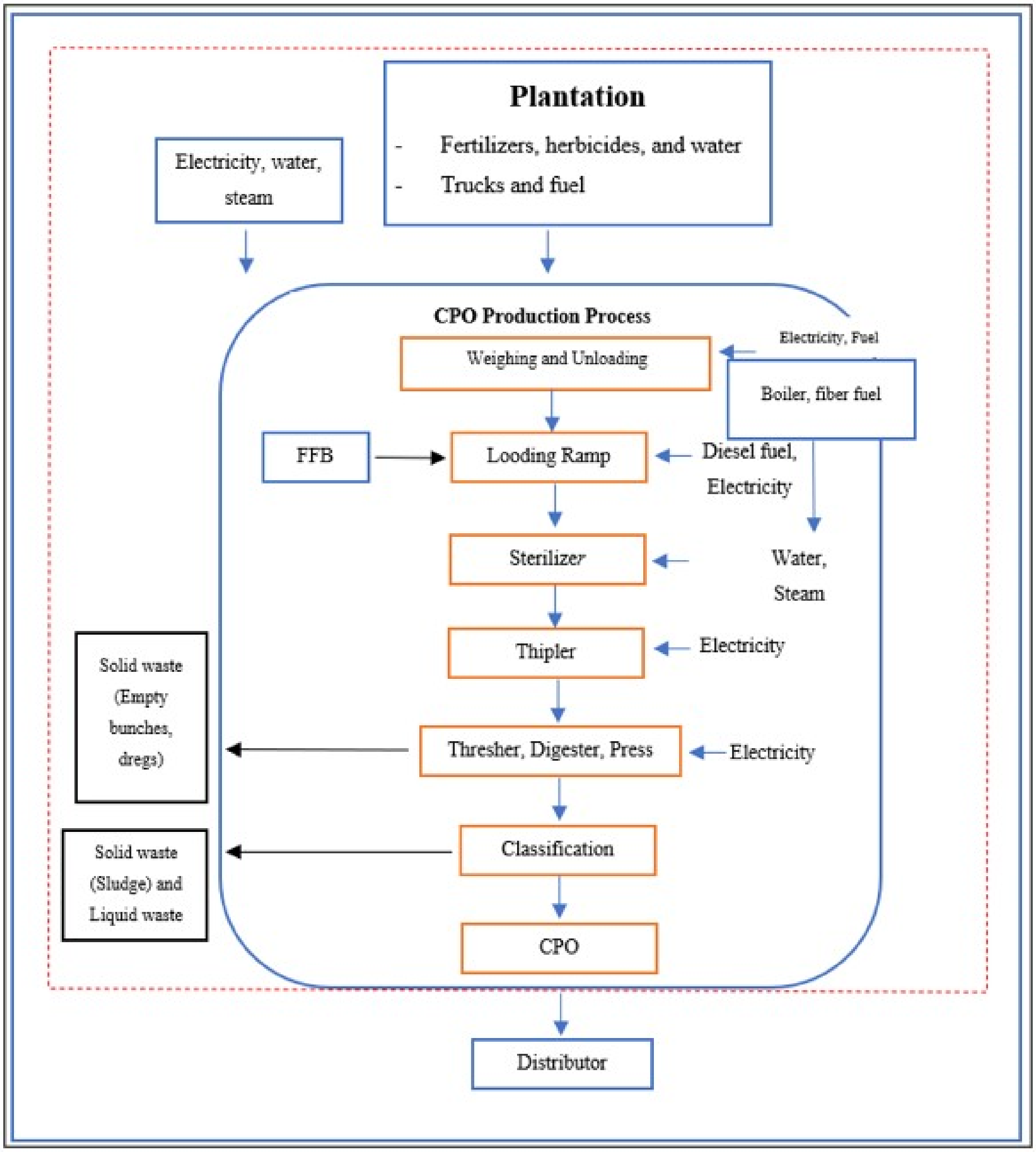

Figure 2. LCI Flow Diagram

and their relationships. The thickness of the red lines in the network indicates the magnitude of the environmental impact. At the same time, the box in the middle shows the level of an activity's environmental impact. Based on the network in Figure 3, the loading ramp process is indicated by the thickest red line among the processes. This indicates that the loading ramp is the stage with the greatest environmental impact. The characterization values for these impacts are shown in Table 4.

Table 4 explains the environmental impact characterization values of 1 ton of CPO. The environmental impact values for each impact category are: GWP (100a) 2×10^4 kg CO_2 eq., acidification 18.5 kg SO_2 eq., eutrophication 7.8 kg PO_4 eq.

The loading ramp process has the greatest impact on the environment, with the highest values in the three impact categories analyzed, namely GWP100a at 1.37×10^4 kg CO_2 eq. (68.7%), acidification of 12.2 kg SO_2 eq. (66%), and eutrophication of 3.17 kg PO_4 eq. (40.7).

The environmental impact results from the classification process, as recorded in Table 4, are slight. The classification process separates only oil, sludge, and wastewater, so only wastewater has an impact; minimal eutrophication emissions are calculated after the calculation.

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Table 1. Emission Factors

Process	Parameter	Data Type	Unit
	Raw Material Transportation Distance*		
	Transportation of FFB		
	PG 20	19	km
	Emission of Diesel Fuel**		
	Nitrogen Oxide (NOx)	5.68	g/kg fuel
	Non-Methane Volatile Organic Compound (NMVOC)	2.32	g/kg fuel
	Carbon Monoxide (CO)	72	g/kg fuel
	Carbon Dioxide (CO_2)	3200	g/kg fuel
	Methane (CH_4)	0.06	g/kg fuel
	Electricity Use Emissions**		
	Carbon Dioxide (CO_2)**	0.774389	kg CO_2/kWh
	Methane (CH_4)**	1.59×10^{-5}	kg CH_4/kWh
	Dinitrogen Oxide (N_2O)**	8.77×10^{-6}	kg N_2O/kWh
	Nitrogen Oxide (NOx)***	0.002	kg NOx/kWh
	Carbon Monoxide (CO)***	7.6×10^{-6}	kg CO/kWh
	Antimony (Sb)***	0.001971	kg Sb/kWh
	Sulfur Dioxide (SO_2)***	0.003438	kg SO_2/kWh
	Phosphate (PO_4^{3-})***	0.000405	kg PO_4^{3-}/kWh
	Fertilizer Use Emissions**		
	Dinitrogen Oxide (N_2O)***	0.01	kg N_2O
	Ammonia (NH_3)***	0.1–0.2	kg NH_3
	Phosphate (PO_4^{3-})***	20–30% leaching	kg PO_4^{3-}
	Sulfur Dioxide (SO_2)***	0.1–0.3%	kg SO_2
	Emissions from Herbicide and Pesticide Use*****		
	Glyphosate	41	%
	Glyphosate Density	1	kg/L g/ml
	Emissions from Active Materials	60–90	%
	Sulfur Dioxide (SO_2)	0.5%	kg SO_2

Source: Google Earth (2025)
** US EPA (2014)
*** IPCC (2006)

3.4.2 Normalization

The normalization process is carried out using normalization factors, which can take the form of characterization factors, weighting factors, or other normalization factors, in accordance with the CML-IA Baseline method. These factors convert the calculated impact results across categories into a uniform set of units or scales. Thus, comparisons of the environmental impacts of various products, services, and activities can be more easily carried out. The normalization results are shown in Table 5.

Table 5 shows that the dominant impact category with the highest value is GWP100a. The process that contributes most to the GWP100a impact category is the loading ramp process. The least impactful category is EP.

3.5 Interpretation

Interpretation in LCA analysis plays an important role in understanding and interpreting the results. In the final phase, the results of the inventory and impact assessments were amalgamated. This integration supports the formulation of meaningful conclusions and targeted recommendations (Schinas et al., 2026). In addition, the interpretation stage also involves sensitivity analysis and effective communication of results to stakeholders.

3.5.1 Comparative Analysis

The comparative analysis was conducted by comparing environmental impacts at each stage of the production process, thereby providing an overview of differences in impact across process units. The results of the comparative analysis for each impact category are shown in Figures 2, Figure 3,

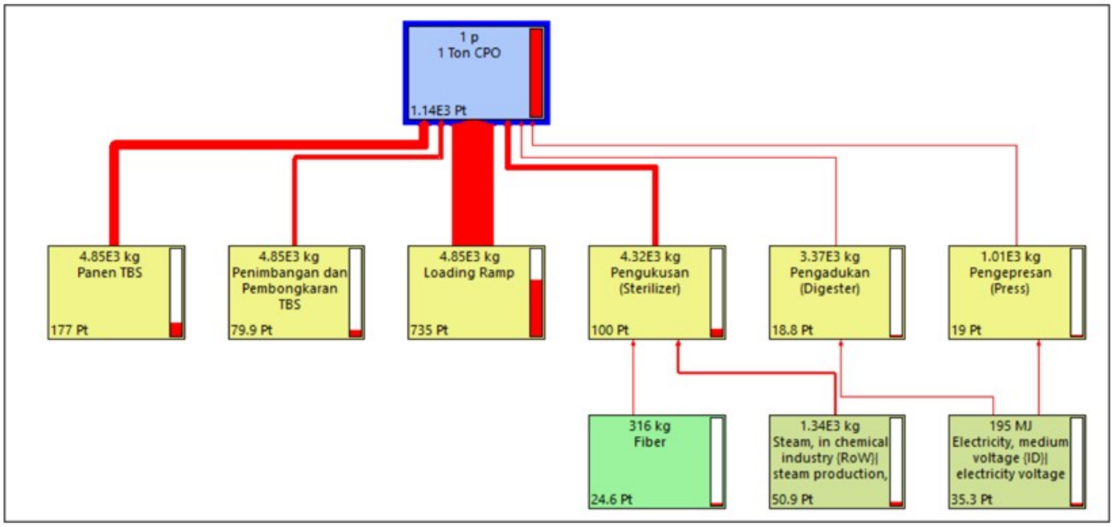

Figure 3. MODFLOW Transient Drawdown Time Series at Three Monitoring Well Distances

Table 2. Life Cycle Inventory (LCI) of Plantation Sub-System (Per Functional Unit)

Process	Parameter	Amount	Unit
Input	NPK 15-15-15 Fertilizer (2 rounds)	0.1275	ton
	Borate	0.0105	ton
	Herbicide	0.00032	ton/Ha
	Water	0.0681	ton/Ha
Output	N_2O	0.00019	ton
	NH_3	0.00287	ton
	PO_4^{3-}	0.00383	ton
	K	0.01588	ton
	glyphosate	7.87×10^{-5}	ton
	SO_2	0.00038	ton
Input	Raw Material		
	FFB	4.854	ton
	Transportations of Raw Materials		
	Transportation FFB	92.226	tkm
	Solar	2	Liter
Output	Raw Material		
	FFB	4.854	ton
	Diesel Fuel		
	Nitrogen Oxide (NOx)	5.68×10^{-3}	ton/kg fuel
	Non-Methane Volatile Organic		
	Compound (NMVOC)	2.32×10^{-5}	ton/kg fuel
	Carbon monoxide (CO)	7.20×10^{-2}	ton/kg fuel
	Carbon dioxide (CO_2)	3,200	ton/kg fuel
	Methane (CH_4)	6.00×10^{-5}	ton/kg fuel

Figure 4, and Figure 5.

1. GWP 100a

   The comparison results in Figure 4 show that the loading ramp process has the most significant impact on GWP100a, amounting to 1.37×10^4 kg CO_2-eq. The loading process on the runway requires 5 liters of diesel fuel for 4,854 tons of fresh fruit bunches (FFB) on a wheel loader used to push the fresh fruit bunches onto the scraper conveyor, and uses electricity on the scraper conveyor. The use of diesel fuel results in greenhouse gas emissions of CO_2, CO, and CH_4. The second-highest-impact process is harvesting, with an

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Table 3. Life Cycle Inventory (LCI) of Milling Sub-system (Per Functional Unit)

Process	Parameter	Amount	Unit
Input	Dump Truck + FFB	9.194	ton
	Electrical Energy (Scales)	0.1	kWh
	Solar Demolition	1	Liter
Output	Empty Dump Truck	4.34	ton
	FFB	4.854	ton
	CO_2	0.077439	kg
	CH_4	0.000002	kg
	N_2O	0.000001	kg
	NOx	0.0002	kg
	CO	0.000001	kg
	Antimony	0.00234	kg
	SO_2	0.00408	kg
	Phosphate	0.00048	kg
	Nitrogen Oxide (NOx)	2.64×10^{-3}	ton/kg fuel
	Non-Methane Volatile Organic Compound (NMVOC)	1.08×10^{-3}	ton/kg fuel
	Carbon monoxide (CO)	3.35×10^{-2}	ton/kg fuel
	Carbon dioxide (CO_2)	1.49×10^{2}	ton/kg fuel
	Methane (CH_4)	2.79×10^{-5}	ton/kg fuel
Input	FFB	4.854	ton
	Solar wheel loader	5	Liter
	Electrical Energy (scraper conveyor)	1.19	kWh
Output	FFB	4.854	ton
	Nitrogen Oxide (NOx)	2.43×10^{-2}	ton/kg fuel
	Non-Methane Volatile Organic Compound (NMVOC)	9.91×10^{-3}	ton/kg fuel
	Carbon monoxide (CO)	3.08×10^{-1}	ton/kg fuel
	Carbon dioxide (CO_2)	1.37×10^{-1}	ton/kg fuel
	Methane (CH_4)	2.56×10^{-3}	ton/kg fuel
	CO_2	0.91884	kg
	CH_4	0.000002	kg
	N_2O	0.000001	kg
	NOx	0.00237	kg
	CO	0.000001	kg
	Antimony	0.00234	kg
	SO_2	0.00408	kg
	Phosphate	0.00048	kg
Input	FFB	4.854	ton
	Boiler	1.335	ton steam
	Fiber	316.4	kg
	Depreciation	11	%
Output	Boiled Loose Beans	4.320	ton
	CO_2	463.3362	kg
	NOx	0.0185	kg
	CH_4	0.0139	kg
	N_2O	0.0185	kg
Input	Boiled Loose Beans	4.320	ton
	Electrical Energy (Tippler machine)	1.06	kWh
Output	Boiled Loose Beans	4.320	ton
	CO_2	0.81775	kg

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	CH_4	0.000002	kg
	N_2O	0.000001	kg
	NOx	0.00211	kg
	CO	0.000001	kg
	Antimony	0.00208	kg
	SO_2	0.00363	kg
	Phosphate	0.00043	kg
Input	Boiled Loose Beans	4.320	ton
	Electrical Energy (Thresher Machine)	1.44	kWh
Output	Empty Bunches	0.950	ton
	Loose Fruit	3.370	ton
	CO_2	1.11512	kg
	CH_4	0.000002	kg
	N_2O	0.000001	kg
	NOx	0.00288	kg
	CO	0.000001	kg
	Antimony	0.00284	kg
	SO_2	0.00495	kg
	Phosphate	0.00058	kg
Input	Loose Fruit	3.370	ton
	Electrical Energy (Digester Machine)	26.96	kWh
Output	Loose Fruit	3.370	ton
	CO_2	20.87753	kg
	CH_4	0.00043	kg
	N_2O	0.00024	kg
	NOx	0.05392	kg
	CO	0.00021	kg
	Antimony	0.05317	kg
	SO_2	0.09269	kg
	Phosphate	0.01092	kg
Input	Loose Fruit	3.370	ton
	Electrical Energy (Press Machine)	26.96	kWh
Output	Dregs	2.359	ton
	Oil	1.011	ton
	CO_2	20.87753	kg
	CH_4	0.00043	kg
	N_2O	0.00024	kg
	NOx	0.05392	kg
	CO	0.00021	kg
	Antimony	0.05317	kg
	SO_2	0.09269	kg
	Phosphate	0.01092	kg
Input	Oil	1.011	ton
Output	CPO	1.006	ton
	Wastewater	0.0051	ton
	Mud	0.000003	ton
	BOD	1.97	kg
	COD	3.38	kg
	Oil, Fat	0.12	kg
	Pb	0.13684	kg
	Cu	0.08036	kg
	Cd	0.00695	kg
	Zn	0.00363	kg
	CH_4	0.6764	kg

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Table 4. Characterization of the Environmental Impact of 1 Ton of CPO

Product Process CPO	Environmental Impact		
	GWP kg CO_2-eq	Acidification kg SO_2-eq	Eutrophication kg PO_4-eq
Oil palm maintenance	21.4	0.0869	2.83
%	0.107	0.47	36.3
Harvest	3.22×10^3	2.9	0.75
%	16.2	15.7	9.62
Weighing and unloading	1.49×10^3	1.33	0.345
%	7.47	7.21	4.42
Loading Ramp*	1.37×10^4	12.2	3.17
%	68.7	66	40.7
Sterilizer	1.40×10^3	1.4	0.271
%	7.02	7.6	3.47
Tippler	2.07	0.0105	0.0081
%	0.0103	0.057	0.104
Thresher	2.8	0.0143	0.0109
%	0.014	0.0772	0.14
Digester	52.4	0.267	0.205
%	0.262	1.45	2.63
Press	53	0.27	0.207
%	0.265	1.46	2.66
Classification	0	0	0.000191
%	0	0	0.00245
Total	2×10^4	18.5	7.8
%	100	100	100

Description: *highest impact

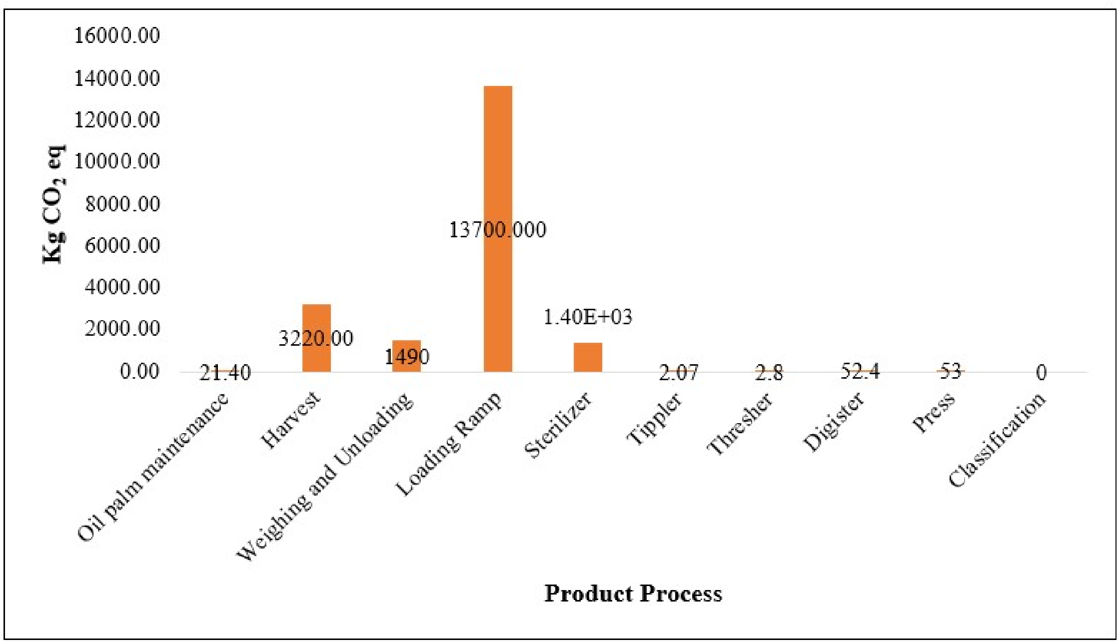

Figure 4. Comparison of the Impact of GWP100a 1 Ton of CPO

impact of 3.22×10^3 kg CO_2-eq. The third process that has the. The greatest impact on GWP100a is the weighing and unloading process, amounting to 1.49×10^3 kg CO_2-eq.

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Table 5. Environmental Impact Normalization of 1 Ton of CPO

Product Process	Environmental Impact		
	GWP	Acidification	Eutrophication
Oil palm maintenance	4.26×10^{-12}	3.08×10^{-12}	2.14×10^{-10}
%	0.107	0.47	36.3
Harvest	6.42×10^{-10}	1.03×10^{-10}	5.69×10^{-11}
%	16.2	15.7	9.62
Weighing and unloading	2.97×10^{-10}	4.73×10^{-11}	2.61×10^{-10}
%	7.47	7.21	4.42
Loading Ramp*	2.73×10^{-9}	4.33×10^{-10}	2.40×10^{-10}
%	68.7	66	40.7
Sterilizer	2.79×10^{-10}	4.98×10^{-11}	2.05×10^{-11}
%	7.02	7.6	3.47
Tippler	4.11×10^{-13}	3.74×10^{-13}	6.14×10^{-14}
%	0.0103	0.057	0.104
Thresher	5.57×10^{-13}	5.06×10^{-13}	8.29×10^{-13}
%	0.014	0.0772	0.14
Digester	1.04×10^{-11}	9.48×10^{-12}	1.55×10^{-11}
%	0.262	1.45	2.63
Press	1.05×10^{-11}	9.59×10^{-12}	1.57×10^{-11}
%	0.265	1.46	2.66
Classification	0	0	1.45×10^{-14}
%	0	0	0.00245
Total	3.97×10^{-9}	6.56×10^{-10}	5.91×10^{-10}
%	100	100	100

Description: *highest impact

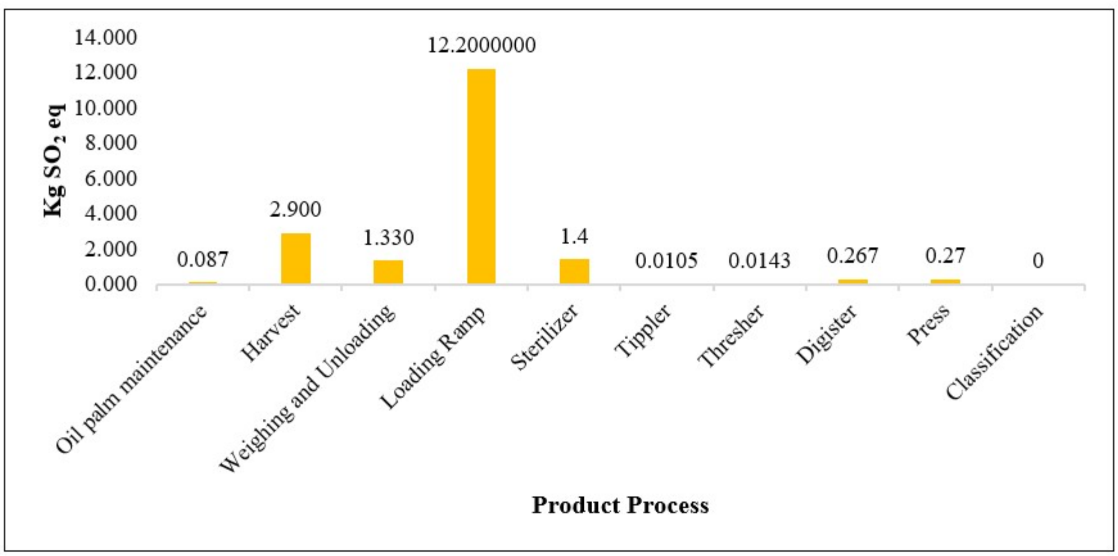

Figure 5. Comparison of the Impact of Acidification of 1 Ton of CPO

2. Acidification
   The results of the comparison for the acidification environmental impact category are shown in Figure 5. The figure shows that the loading ramp stage has the most significant environmental impact on acidification, amounting to 12.2 kg SO_2-eq because loading and unloading activities with wheel loaders using diesel fuel produce NOx and SO_2 emissions, plus electricity consumption from sources from the PLTU, which increases the contribution of acidification. The second stage that has an environmental impact of acidification is the harvesting process, with an impact value

Table 6. Impact Contribution of the Production Process of 1 Ton of CPO

Product Process	Environmental Impact		
	GWP	Acidification	Eutrophication
Oil palm maintenance	4.26×10^{-12}	3.08×10^{-12}	2.14×10^{-10}**
Harvest	6.42×10^{-10}**	1.03×10^{-10}**	5.69×10^{-11}
Weighing and unloading	2.97×10^{-10}	4.73×10^{-11}	2.61×10^{-11}
Loading Ramp	2.73×10^{-9}*	4.33×10^{-10}*	2.40×10^{-10}*
Sterilizer	2.79×10^{-10}	4.98×10^{-11}	2.05×10^{-11}
Tippler	4.11×10^{-13}	3.74×10^{-13}	6.14×10^{-14}
Thresher	5.57×10^{-13}	5.06×10^{-13}	8.29×10^{-13}
Digester	1.04×10^{-11}	9.48×10^{-12}	1.55×10^{-11}
Press	1.05×10^{-11}	9.59×10^{-12}	1.57×10^{-10}
Classification	0	0	1.45×10^{-14}
Total	3.97×10^{-9}	6.56×10^{-10}	5.91×10^{-10}

Description: *greatest impact
**second greatest impact

Table 7. Data Changes in Sensitivity Analysis

Process	Parameters	Initial	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Input	Wheel Loader Diesel Fuel	5	4.750	4.275	5	5	5	5
Input	Transportation of FFB	92.23	92.23	92.23	87.615	78.853	92.23	92.23
	Diesel Fuel	2	2	2	1.9	1.8	2	2
Input	Fertilizer NPK 15-15-15	0.12752	0.12752	0.12752	0.12752	0.12752	0.121	0.115
	Fertilizer Borate	0.01053	0.01053	0.01053	0.01053	0.01053	0.010	0.009

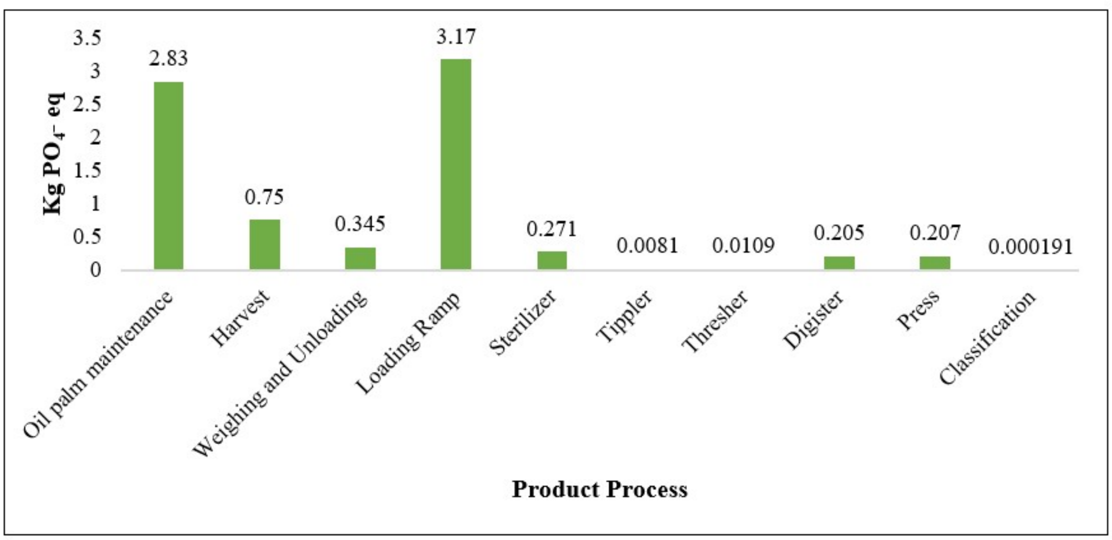

Figure 6. Comparison of the Impact of Eutrophication from 1 Ton of CPO

of 2.9 kg SO_2-eq eq due to the use of fertilizers and herbicides.

3. Eutrophication
The results of the comparative analysis for the eutrophication impact category are shown in Figure 6. The loading ramp process is the stage that contributes the most to eutrophication, generating 3.17 kg PO_4-eq per ton CPO. This is highly attributed to the temporary

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Table 8. Sensitivity Analysis Results

Analysis Results	Impact Category		
	GWP100a	Acidification	Eutrophication
Initial	100%	100%	100%
SV 1	35.55%	38.38%	61.92%
SV 2	31.95%	40.70%	63.46%
SV 3	95%	98.92%	99.36%
SV 4	90%	97.30%	98.72%
SV 5	99.5%	99.46%	76.15%
SV 6	99.5%	99.46%	70%

accumulation of FFB at the loading station, which triggers the generation of nutrient-rich organic leachate containing high concentrations of Nitrogen (N) and Phosphorus (P). Without an adequate secondary containment or wastewater treatment system, this run-off infiltrates local drainage systems and accelerates eutrophication. The second process that contributes the most to eutrophication is oil palm maintenance, with an impact value of 2.83 kg PO_4-eq due to the use of fertilizers and herbicides.

Based on a comparative analysis of various categories of environmental impact, the loading ramp process has the highest environmental impact. This is due to the use of diesel fuel, which has the most tremendous impact. This process has a significant impact on all three categories, namely global warming potential, eutrophication, and acidification.

Comparison of this study with the study by Rinaldo et al. (2023), with cradle-to-gate limitations that also include plantation subsystems and factory processes, reported GWP of 559.9 kg CO_2-eq./ton CPO, AP of 2.043 kg SO_2-eq./ton, and EP 0.963 kg PO_4-eq./ton. The GWP emissions, acidification, and eutrophication results for the XYZ Company are higher than those reported in previous studies. This difference is due to variations in the scope of assessment and in the amounts of utilities, raw materials, additives, and other components used in the impact analysis.

A comparison of this study with Hawari (2021) study focuses on GWP and obtains 1,180 kg CO_2-eq./ton CPO (contribution: plantations 1,069 kg, transportation 49 kg, nurseries 62 kg CO_2-eq./ton). GWP emissions, acidification, and eutrophication in XYZ Company plantations were higher than in previous studies. This is due to differences in the scope of assessment and the amounts of raw materials, additives, and other utilities used in the impact assessment calculations.

This study compares with Sari et al. (2023), which uses a functional unit of 1 kg of CPO and reports annual aggregates per process (e.g., factory/boiler, FFB transportation, fertilization). The GWP in factories is 2.16×10^7 kg CO_2-Eq/kg CPO/year, with a significant contribution from transportation and fertilization in the plantation. Because the results are presented as annual totals per process rather than per 1 kg/ton of CPO, Sari's figures cannot be accurately normalized to 1 ton without annual CPO production data to divide the total. However, in terms of pattern, Sari shows the factory station (especially the boiler/turbine) and transportation as the main contributors to GWP. In contrast, in this study, the main contributors are at the loading ramp stage.

In this study, the highest levels were found at the loading ramp stage. Although it is only a temporary unloading and storage area, it became a hotspot because this is where the initial release of N, P, and organic acids from FFB occurs. N and P compounds contribute significantly to eutrophication, while sulfur, nitrogen, and organic acids contribute to acidification (Ulimaz, 2022). Furthermore, a deep assessment of the Life Cycle Inventory (LCI) provides a strong quantitative justification for why the loading ramp dominates the environmental impacts, particularly GWP 100a. Based on the verified primary data, the operational utility at the loading ramp consumes a substantial amount of fossil energy, specifically 5 Liters of pure diesel fuel via the heavy-duty wheel loader and 1.19 kWh of grid electricity per functional unit. In comparison, the internal transportation of FFB during the harvesting stage only consumes 2 Liters of diesel fuel. From a thermodynamic and environmental modeling standpoint, fossil-diesel combustion releases direct, high-intensity greenhouse gases (3,200 g CO_2/kg fuel), which immediately amplifies the GWP score. Conversely, the steam generation at the sterilizer station primarily utilizes 316.4 kg of biomass fiber as boiler fuel. Under the CML-IA Baseline methodology, carbon emissions from biogenic materials (fiber and shells) are treated as carbon-neutral, causing the steam generation hotspot to appear significantly lower than the fossil-driven loading ramp station. This operational reality at XYZ Company underscores that heavy machinery inefficiencies during internal crop-handling can severely outpace the impacts of traditional factory processing units, justifying the urgent technological need to transition the loading ramp's mobile equipment from conventional diesel to biodiesel.

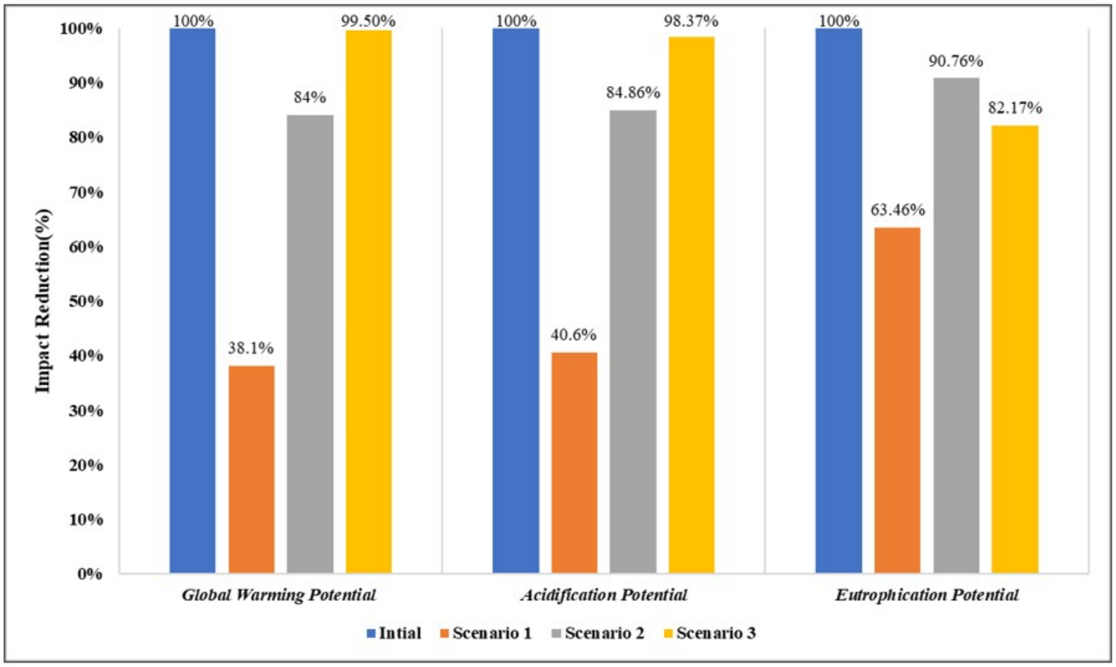

Figure 7. Comparison Results of the Initial Scenario with the Designed Scenario

Table 9. Comparison of Normalization for Each Scenario

Impact Category	Initial	Scenario 1	Scenario 2	Scenario 3
Global Warming Potential (GWP100a)	3.97×10^{-9}	1.52×10^{-9}	3.35×10^{-9}	3.96×10^{-9}
%	100%	38.1%	84%	99.5%
Acidification	6.50×10^{-10}	2.67×10^{-10}	5.59×10^{-10}	6.45×10^{-10}
%	100%	40.6%	84.86%	98.37%
Eutrophication	5.91×10^{-10}	3.75×10^{-10}	5.37×10^{-10}	4.86×10^{-10}
%	100%	63.46%	90.76%	82.17%

3.5.2 Contribution Analysis

Contribution analysis in LCA interpretation helps identify the most impactful areas and evaluate mitigation strategies. The purpose of contribution analysis is to understand the role and magnitude of each element's influence in a product's life cycle. This analysis serves as the basis for determining the most effective improvement measures to reduce environmental impact. The results of the contribution analysis are shown in Table 6. Analysis of dominant contributors based on LCI, as shown in Table 5 for each impact category, is as follows:

1. N_2O, CO_2, and CH_4 emissions mainly influence GWP-100a impact. These three emissions are generated from the use of diesel fuel and electricity in each process of producing 1 ton of CPO. The production process with the highest CO_2 emissions is the loading ramp process, which produces 13,700 tons of CO_2. In addition to CO_2, other gases that contribute to the GWP100a impact are N_2O at 16.32 and CH_4 at 11.3.
2. The primary emissions that contribute to environmental acidification are SO_2 and NOx. These emissions are generated from vehicle fuel combustion, electricity use, and the use of agricultural chemicals. The amount of NOx and SO_2 produced as causes of acidification is 16.8 and 1.6, respectively.
3. Emissions that cause eutrophication are emissions in the air, water, and soil. Air emissions that contribute to eutrophication are NOx at 4.37. Emissions in water and soil that contribute to eutrophication are NH_3 at 2.02 and phosphate at 1.318.

3.5.3 Sensitivity Analysis

The processes that contribute significantly to each impact category, as shown in the contribution analysis, will be further examined through sensitivity analysis and can be used to assess the robustness of the assessment results (Xu et al., 2026). Sensitivity analysis is a method used to determine how changes in specific inputs or assumptions affect results. The loading ramp and harvesting processes were selected for further analysis because they both contribute significantly to environmental impacts. Based on the results of the previous contribution analysis, the components that were reduced from these two processes were fuel combustion in the loading ramp process and raw material transportation and fertilizer use. Diesel fuel was identified as the largest contributor in this process, as shown in Table 5 for 1 ton of CPO.

The value changes in both processes were made by reducing diesel fuel consumption and changing the transportation distance to see how much the changes in the inputs of both processes affected the environmental impact value output. The changes in input values in the production process were based on the assumption of a 5% and 10% reduction in one of the input components. Percentage changes of 5% and 10% were used to represent variations in input data uncertainty in the life cycle inventory (LCI). This range of small to moderate changes was chosen to evaluate the robustness of the model and determine the effect of parameter changes on environmental impact results. This approach aligns with Groen et al. (2017), who emphasized that sensitivity analysis is vital to evaluate the direct effect of input parameter uncertainty on LCA outcomes. In the context of XYZ Company, these 5% and 10% margins represent realistic and highly attainable eco-efficiency optimization targets-such as minor transport driving pattern improvements, routine machinery maintenance schedules, or precision agricultural fertilizer dosing-without requiring a structural operational shutdown or capital-intensive overhauls of the existing plant infrastructure. The results of this sensitivity analysis can be used to identify the most influential parameters in the process. The sensitivity analysis (SA) scenarios for the CPO production process are divided as follows:

a) Scenario 1: reducing diesel fuel consumption by 5% in the loading ramp process.
b) Scenario 2: reducing diesel fuel consumption by 10% in the loading ramp process.
c) Scenario 3: reducing transportation distance and diesel fuel consumption by 5%.
d) Scenario 4: Reduce transportation distance and diesel fuel consumption by 10%.
e) Scenario 5: Reduce fertilizer consumption by 5%.
f) Scenario 6: Reduce fertilizer consumption by 10%.

Table 7 below presents changes in input data for each sensitivity analysis scenario. This table shows variations in diesel fuel consumption parameters during loading ramp and FBB transportation processes, as well as fertilizer use in oil palm maintenance. Each scenario shows a 5% to 10% decrease in input use to determine the extent to which these changes affect emissions and the environmental impact of the CPO production process. The results of the sensitivity analysis are shown in Table 8.

Table 8 shows that the five scenarios developed by reducing specific components differ in environmental impact values. Scenarios 1 and 2 involve reducing diesel fuel consumption in wheel loaders at the loading ramp stage by 5% and 10%, resulting in reductions in environmental impact of 38.08%-64.45% for scenario 1 and 36.54%-68.05% for scenario 2. The most significant reduction in Scenario 1 occurred in the GWP 100a impact, which decreased by 64.45%. The largest reduction in Scenario 2 occurred in the GWP 100a impact, which decreased by 68.05%.

Scenarios 3 and 4 involve reducing the distance traveled to transport raw materials by 5% and 10%, resulting in reductions in environmental impact of 0.64%-5% for scenario 3 and 1.28%-10% for scenario 4. Scenario 5 involves a 5% and 10% reduction in fertilizer use in the palm oil maintenance process, resulting in a reduction in environmental impact of between 0.5% and 23.85% for scenario 5 and 0.5% to 30% for scenario 6. The design of these six scenarios shows that all three processes are sensitive to changes in impact.

An uncertainty analysis was conducted to evaluate the reliability of the life cycle inventory (LCI) data used in the study. Uncertainty can primarily stem from variations in operational data, energy consumption, and the assumptions used in the LCA modeling. However, the use of primary data obtained directly from PT XYZ's operations and the verification process against company documents demonstrated a good level of consistency and representativeness. Furthermore, the sensitivity analysis results indicated that changes in input parameters did not significantly alter the pattern of environmental impact results, the model was deemed sufficiently robust and the research results can be considered reliable.

3.5.4 Improvement Analysis

The improvement analysis aims to determine the optimal scenario to minimize the environmental impact of the CPO production process at XYZ Company. The results of the sensitivity analysis show that the use of diesel fuel for wheel loaders in the loading ramp process, reducing the distance for transporting raw materials, and the use of fertilizers during oil palm maintenance are the main focuses of improvement. Improvement recommendations that can be implemented by XYZ Company in reducing environmental impact, based on sensitivity analysis, include several approaches, namely:

1. The transportation of raw materials by diesel-fueled vehicles has an environmental impact from fuel combustion. A recommended improvement is to switch from diesel fuel to biodiesel. The use of biodiesel in vehicles can reduce SO_2 by 15.62%, CO_2 by 23.21%, and hydrocarbons by 2.91% (Wirawan et al., 2014).
2. Reducing transportation distances also means reducing fuel consumption. Less fuel burned means fewer greenhouse gas emissions, especially CO_2, the primary product of fuel combustion and a chain driver of other emissions. For example, optimizing routes through the Global Positioning System (GPS), as XYZ company has many internal routes from the plantation to the factory. With the help of the GPS and digital maps, the company can analyze which routes are most optimal in terms of distance and road conditions to reduce

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travel distance and fuel consumption (Nematollahi et al., 2024).
3. Using 750 g of bio-fertilizer can reduce the standard dose by 75%, with the reduced standard dose responding similarly to the 100% standard dose treatment (Khairulya and Sudradjat, 2016).

Based on this improvement analysis, the following improvement scenarios were designed:

1. Initially, the scenario describes conditions without modification in processes with high contributions.
2. Scenario 1: replacing diesel fuel with biodiesel fuel.
3. Scenario 2, reducing the distance traveled to transport raw materials by increasing route efficiency by 35-40% using a GPS and automatically reducing diesel fuel consumption (Nematollahi et al., 2024).
4. Scenario 3: Using 750 g of bio-fertilizer can reduce the standard dose by 75% while still providing physiological and morphological responses comparable to the complete 100% standard dose treatment (Khairulya and Sudradjat, 2016).

The results of the comparison for each scenario are shown in Table 9 and Figure 7.

Table 8 presents the comparative analysis of the environmental impacts of the recommended improvement scenarios. The analysis shows a reduction in impact across all scenarios. Scenario 1, which involves replacing diesel fuel with biodiesel, can reduce environmental impact by 38.1%-63.46% in each impact category. The impact category with the most significant reduction in environmental impact is global warming potential, with a value of 38.1%. Scenario 2, which reduces the distance traveled by raw materials by increasing route efficiency by 40%, can reduce environmental impact by 84%-90.76%. The most significant reduction in impact occurred in global warming potential, with an 84% reduction. Scenario 3, which involves reducing fertilizer use by 75% and using 750 g of bio-fertilizer with biological fertilizer, can provide an environmental impact value of 82.17%-99.5%. The most significant reduction in impact occurred in eutrophication impact, with a value of 82.17%. Based on these scenarios, the optimal approach to improving environmental quality and the sustainability of CPO products at XYZ company is scenario 1: replacing diesel with biodiesel.

3.5.5 Data Validation, Reliability, and Uncertainty Discussion

To ensure the reproducibility and credibility of the LCA outputs, all primary data collected from XYZ Company (including fuel logs, fertilizer procurement receipts, and electricity bills) underwent a rigorous data validation process. Material and energy balance equations were cross-checked with the plant's daily operational capacities. To address data quality and potential geographical uncertainties, a data reliability check was integrated. While primary agricultural and utility inputs represent highly reliable, site-specific field measurements, secondary background data utilized from the Ecoinvent database introduces minor geographical uncertainties (e.g., global averages for herbicide production chains). However, the consistency of the CML-IA Baseline method across all modeled processes minimizes structural mathematical variance, ensuring that the identified hotspots provide a statistically sound baseline for environmental decision-making.

4. CONCLUSIONS

The life cycle of 1 ton of CPO at XYZ Company uses a cradle-to-gate approach and covers the plantation subsystem to processing at the mill. Impact characterization at the environmental impact assessment stage resulted in a global warming potential of 2×10^4 kg CO_2 eq., acidification of 18.5 kg PO_4 eq., and eutrophication of 7.8 kg SO_2-eq. The greatest impact occurs at the loading ramp stage. Recommendations to minimize the environmental impact of producing 1 ton of CPO are replacing diesel fuel with biodiesel fuel, reducing raw material transportation distance by 40% by using GPS, and optimizing the use of inorganic fertilizers by replacing them with biofertilizers (for example, using 750 g of biofertilizer can reduce the standard dose by up to 75%). The scenario of replacing diesel with biodiesel was identified as the most effective, capable of reducing global warming potential by up to 61.9%.

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