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Regional Case Study

Life Cycle Assessment in Crude Palm Oil Production: Optimization of Oil Extraction Rate

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Abstract

Indonesia, as the foremost producer of palm oil globally, faces crucial environmental challenges. Besides palm oil production plays an important role in economic growth and national development, it also has environmental consequences from the production process. Crude Palm Oil (CPO) Industries face challenges balancing economic growth and environmental sustainability. This research carries out an environmental impact analysis of CPO production with the Life Cycle Assessment method using openLCA software 2.03 with CML-IA Baseline and ReCiPe 2016 Midpoint (H). Scope of this research adopts cradle-to-gate analysis with declaration unit of 1 kg CPO product. In this analysis, it was found that CPO production had a significant impact on GWP, Terrestrial Eco-toxicity Potential, and Land Use Change. So this research also explores the environmental impact of increased Oil Extraction Rate (OER) scenario with an OER of 21% and 22% compared to OER in current production activities. The research showed that all impacts decreased when OER was increased, impacts decreased of around 3% at OER 21% and decreased of around 8% at OER 22%. These findings confirm the potential feasibility of implementation based on increasing OER in the Palm Oil Industry to achieve targets for sustainable improvement.

Keywords: Crude palm oil; environmental performance; life cycle assessment; oil extraction rate; sustainability improvement

1. Introduction

Palm oil is one of the plantation sub-sectors that is essential to Indonesia, especially in economic activities. The palm oil market is large, encompassing both the food and non-food industries. Industries that use palm oil as the raw material in their production processes are the fractionation industry (especially the cooking oil industry), special fats (cocoa butter substitute), margarine/shortening, oleo-chemicals, and bath-soap (Directorate of Food Crops, Horticulture, and Estate Crops Statistics, 2023). The United States Department of Agriculture (USDA) (2024) reported that global crude palm oil production will reach approximately 76 million metric tons by 2020. Palm oil production increased year by year, reaching 79.48 million metric tons in 2023/2024 from around 73 million metric tons in the previous year. Indonesia is the largest palm oil producer with 59% of total global production in 2023/2024, followed by Malaysia at 24% (USDA, 2024). Indonesia and Malaysia are the two main countries leading exports of crude palm oil and its derivative products. Palm oil exports from Indonesia in 2022 reached almost 29.75 billion US dollars (Statistics Indonesia, 2022). The bustling palm oil export activity signifies the industry's development and serves as a cornerstone in driving national development and fostering significant economic growth (Purnomo et al., 2020). The high market demand for palm oil encourages the production of palm oil on a large scale, thus opening opportunities for economic diversification.

The extent of palm oil plantations in Indonesia has a major influence on the overall volume of palm oil production (Zuhdi et al, 2020). Based on data provided by the Directorate General of Estates (2023), the area of palm oil plantations in Indonesia in 2023 is estimated to reach 16,834 thousand hectares, with oil palm production reaching 48,235 thousand tons and productivity of 4,139 kg/ha. The palm oil production presented in that publication is primary production that transforms empty fruit bunches into semi-finished goods known as Crude Palm Oil (CPO) which has a higher economic value. In 2023, CPO production in Indonesia increased rapidly, reaching around 36,287 thousand tons or an increase of 14.8% compared to 2022 (Indonesian Palm Oil Association, 2023). The potential of palm oil in Indonesia is very large and continues to increase every year. However, the expansion and increase in the potential of the palm oil industry must focus on environmental and sustainability aspects to ensure a balanced and sustainable business in the long run. While increasing CPO production in Indonesia has a positive impact on economic and industrial growth, environmental challenges also need to be addressed. A holistic approach is needed to achieve sustainability development in the palm oil industry. One important step is to strengthen sustainable agricultural practices, including environmentally friendly land management, monitoring water use efficiency, and controlling greenhouse gas emissions during the production process. These steps can help reduce negative impacts on the environment on the environment (Muhie, 2022; Maraveas et al., 2023).

The palm oil production is closely linked with environmental issues. In the land clearing and expansion activities of palm oil plantations, the oil palm industry impacts the environment, resulting in habitat destruction and the loss of biodiversity (Azeez, 2023). Indirect land use changes due to the palm plantation expansion impact the local hydrology and biotic components of these ecosystems (Murphy, 2019). Land clearing cannot be separated from the potential impact of greenhouse gases (Slamet, 2020). Human agricultural activities, such as deforestation and altering the land's natural use, frequently contribute to greenhouse gas potential, which includes carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen monoxide (NO), nitrogen dioxide (NO_2), methane gas (CH_4), and chlorofluorocarbons (CFC) (Borrelli et al. 2020). Peatland management activities, burning biomass, and deforestation produce large amounts of carbon dioxide (CO_2), thereby contributing to climate change and global warming (Ahmad et al., 2023; Nurhayati et al., 2022). Furthermore, methane and nitrous oxide, the two greenhouse gases that affect climate change, can be found in palm oil plantations and the palm oil industry (Karini et al., 2022; Meijaard et al., 2020; Maskun et al., 2021). Once forests are cut down and peatlands are drained for oil palm, massive amounts of carbon dioxide are produced. The deforestation and conversion of land to palm crops have a major impact on the local and regional climate (Nnamchi et al., 2022). Another emission that emerges from the development of palm coconut is that there is a potential increase in isoprene production by palm trees that can affect atmospheric chemistry, cloud cover, and rainfall. (Nadzir et al, 2020). Palm oil extraction process contributes to the environment by generating emissions that affect water and soil. Palm oil production produces POME which is classified as an emission to water, while shells, palm kernel, fibre, and ash are emissions to soil that are discharged to the ground and have the potential to contribute to soil pollution (Egberi, 2022; Le et al., 2022; Wahyono et al., 2020). Indonesia was the seventh largest emitter in the world in 2009 for pollutant emissions contributing roughly 30% of emissions linked to global warming due to the effects of deforestation. Besides that, from 2000 to 2010, the palm oil sector in Indonesia contributed 2-9% of total emissions as an outcome of utilizing tropical land for oil palm cultivation. Subsequently, the palm oil industry in Indonesia has grown massively and contributed to 18-22% of the country's CO_2 emissions in 2020 as a result of plantation development in Kalimantan (Carlson et al. 2018; Murphy et al., 2021).

The industry is encouraged to make improvements that can be implemented consistently with the aim of reducing emissions generated from all activities both from the upstream process of plantations and CPO production activities in the core process. Zhao et al (2023) have developed a model for palm oil production by optimizing palm oil productivity in plantation areas using established age-related rates of production and replanting at 25 years after the previous palm oil is cut down. In Malaysia, research has been carried out regarding the potential for optimal replanting levels for long-term production using a system dynamics approach that combines dynamic interactions between palm oil supply and demand, new plantation area, and crude palm oil prices (Faeid et al., 2020).m Fosch et al (2023), also analyzed the potential for sustainable improvement by replanting unproductive oil palms in smallholder plantations in Sumatra, Indonesia. In addition to potential improvements in the plantation area, improvements are also very necessary in the mill to increase the CPO production capacity in the factory. According to Baharuddin et al (2022) who have investigated one of the palm oil companies in Indonesia, improvements such as increasing the capacity of production machinery to increase CPO production, as well as improving product quality are needed to increase the competitiveness of the company. Chew et al (2021) also made continuous improvements to create high milling efficiency with improved oil extraction rate (OER). OER is an important parameter that determines the quality of CPO production. Palm oil mills use Oil Extraction Rate (OER) as an indicator of production efficiency that calculated by comparing the total crude palm oil extracted with the total fresh fruit bunches processed in the mill. There are various ways to optimize oil extraction from fruit bunches including Soxhlet extraction, ultrasonic treatment, supercritical fluid extraction, enzymatic technology, MICRONES, and decoring (Silvamany et al, 2021; Chew et al., 2021). Therefore, to encourage the palm oil industry to achieve sustainable development targets, this research is needed to explore the environmental performance assessment of improvement strategies with OER improvement in the palm oil industry sector. The objectives of this study are to (i) determine the value of the environmental performance of CPO production activities in current conditions and (ii) explore the potential environmental performance with OER improvement scenarios using the LCA method with openLCA software to analyze opportunities for sustainable improvement based on the OER.

2. Methods

2.1. Environmental Performance Analysis with Life Cycle Assessment (LCA)

The research uses a LCA approach in evaluating the environmental impact of the CPO production process. LCA is a method used to assess the environmental impact aspects of a product throughout its entire life cycle (Ogunmilua et al., 2021). In this analysis, the LCA assesses the environmental performance obtained from all Crude Palm Oil production activities, starting from the raw materials extraction process until the palm oil extraction process to the final product that will be marketed. In this study, LCA plays a role in analyzing the impact on production activities under normal extraction conditions. Then, the current conditions become the baseline for further analysis regarding the calculation of environmental impacts on improvement scenarios to see whether that scenario has the potential to improve environmental performance in crude palm oil production or for industrial palm oil widely. It is hoped that the environmental impact results from comparing current conditions with this scenario will provide information regarding efforts to the sustainability improvement of Palm Oil production based on life cycle analysis. The LCA study was carried out in stages that followed specific standards and guidelines to ensure data consistency and transparency, consisting of 4 main stages based on the ISO 14040 and ISO 14044 standards, included determining the goal and scope, life cycle inventory, life cycle impact assessment, and interpretation stage.

2.1.1. Goal and Scope

The goal and scope phase is a very important stage in the LCA, this stage determines the scope limits for determining the direction of the study. Goals and scope guide the consistency of life cycle analysis, which determines the system boundary, the process, the data required, and the functional units as the basis for all data collection, modeling, and impact evaluation. 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. 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 is 1 (one) kilogram of the product, which covers 100% of the total Crude Palm Oil (CPO) product produced. The total product of the CPO-producing for one year is 135,794,850 kg, which was then used as a reference flow in this LCA study. The system boundary for CPO production based on PCR is the cradle-to-gate analysis scheme, consisting of two life cycle stages: upstream and core process. The system boundary is also based on the type of final product produced, namely CPO, which is an intermediate product (raw material for other processed products) so that the end-of-life scenario is in the next product.

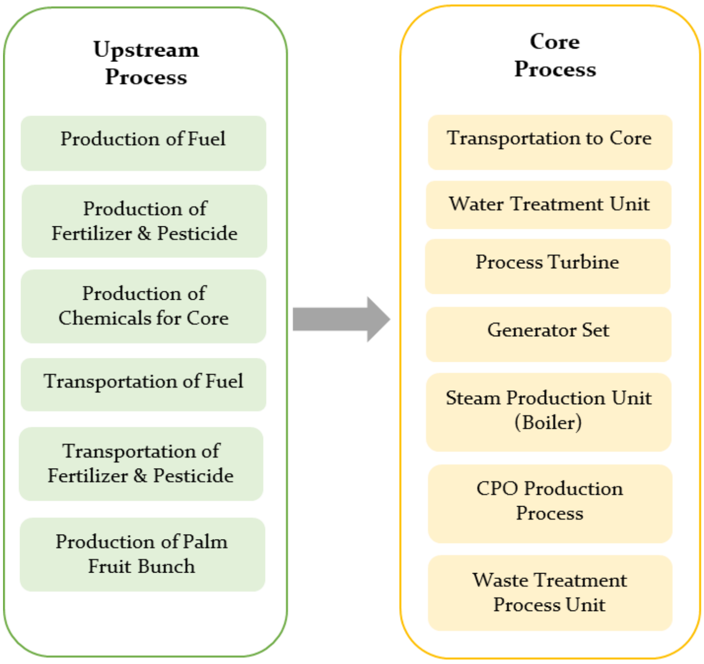

Figure 1. System boundary of CPO production

2.1.2. Life Cycle Inventory

The inventory analysis phase contains steps to collect data and determine the inputs and outputs from the product system. This process allows us to understand the resource usage and releases to the environment of the entire production process according to predefined system constraints. Identify and collect data related to the palm oil production process, including information regarding resources such as energy, water, raw materials, and chemical materials, as well as the output such as products, waste, and emissions that are released into the environment. Data was collected from reliable sources and complies with system constraints. The data used in this analysis was divided into two types of data that are primary data (88%) which is actual industry data were collected and measured directly by the palm oil industry for 1 year period, in this case, from January to December 2022 and secondary data (12%) obtained from the Ecoinvent 3.9.1 database.

2.1.3. Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) is a critical phase in Environmental Impact Assessment that evaluates of probable environmental performance of production activity using the data from life cycle inventory results. At this stage, inventory data is linked to specific environmental impacts. This LCIA stage combines inventory data with specific environmental impacts so that it can be analyzed to what extent each step in the product life cycle contributes to the desired environmental impact (Jayasundara and Rathnayake, 2023). The impacts and methods used for assessment depend on the goals and scope of the research. The inventory analysis phase involves steps to collect data and determine the relevant inputs and outputs from the product system (Lim et al, 2023). In this research, the LCIA methods used include CML-IA Baseline and ReCiPe 2016 Midpoint (H). The LCA analysis was carried out using openLCA software 2.0.3. This software helps calculate and analyze the environmental performance of the life cycle of palm oil products. openLCA software performs detailed calculations and analysis by identifying the main drivers throughout the product life cycle, based on input-output flow categories and production processes, as well as calculating various impact categories and visualizing the results thoroughly. The LCIA stage is a key step in understanding a product's contribution to environmental impact. By using a variety of methods and indicators, this research can provide an in-depth understanding of the environmental impacts of palm oil and enable the identification of areas for improvement to support sustainable practices.

Table 1. Impact categories of crude plam oil production assessment

Impact Category	Reference unit	Impact Calculation Method
Global Warming Potential	kg CO_2 eq	CML-IA Baseline
Acidification Potential	kg SO_2 eq	CML-IA Baseline
Terrestrial Eco-toxicity Potential	kg 1.4-DCB	ReCiPe 2016 Midpoint (H)
Freshwater Eco-toxicity Potential	kg 1.4-DCB	ReCiPe 2016 Midpoint (H)
Human Toxicity Potential	kg 1.4-DB eq	CML-IA Baseline
Land Use Change	m^2a	ReCiPe 2016 Midpoint (H)

2.1.4. Interpretation

This interpretation is the final stage carried out to review the results of the inventory and impact assessment summarized and discussed as a basis for conclusions, recommendations, and decision-making following the goal and scope (Laurent et al, 2020). Interpretation of this research identified environmental impacts with the most significant contribution value from the entire life cycle of CPO products. At the interpretation stage of this research, apart from identifying the impact results of the CPO production process, improvement opportunities were also identified by carrying out a comparative analysis between the impact on current palm oil production activities and the impact results from the improvement scenario.

2.2. Sensitivity Analysis of OER Increase Scenario

The analysis in this study not only calculates the environmental impact of CPO in general but in more detail explores the potential for improving the efficiency of CPO production based on analysis using the results of the impact of the production process under current conditions. Analysis of potential improvements is carried out by comparing the results of the impact assessment with the LCA calculation model. The improvement in this study is focused on the oil extraction rate value used in the CPO production process. Sensitivity analysis was performed to analyze and assess the sensitivity level of scenario changes. The sensitivity analysis in this study was carried out with a scenario of increasing the OER value to 21% and 22% with an OER baseline of 20.19%. The baseline refers to the impact under normal conditions without any changes. The results of this sensitivity analysis will provide an assessment of the changes in the impact of each OER increase scenario that can be implemented by the Palm Oil Industry.

3. Result and Discussion

3.1. Life Cycle Inventory and Modelling

Crude Palm Oil production with a cradle-to-gate scope is devided into two life stages: the upstream process and core process. Upstream processes encompass planting activities, included palm oil plantation management that controlled palm oil plants until sorting fresh fruit bunches. The activities that occur in gardens are fertilizer and pesticide production. To produce high-quality palm fruit bunches, palm oil plants were kept under control using fertilizers and insecticides. The core process includes utility processes, such as water treatment processes to produce processed water; boiler and turbine processes that produce steam; and generator processes that produce electricity. All the products obtained by the utility process were used for FFB processing in the mill process.

Table 2. Summary of inventory in crude palm oil production (per 1 kg CPO)

Input of Upstream Process				Output of Upstream Process		
Category	**Inventory data**	**Amount**	**Unit**	**Inventory data**	**Amount**	**Unit**
Production of-	Fuel	7.72E+06	kg	Fresh Fruit Bunch	4.95E+00	kg
	NPK Fertiliser	2.83E+06	kg			
	Urea	6.62E+04	kg			
	Potassium chloride	4.94E+04	kg			
	Phosphate	2.65E+05	kg			
	Kieserite Fertiliser	7.38E+05	kg			
	Calcium Borates Fertiliser	4.97E+04	kg			
	Herbicide	2.48E+04	kg			
	Pesticides	1.57E+03	kg			
Input of Core Process				**Output of Core Process**		
Category	**Inventory data**	**Amount**	**Unit**	**Inventory data**	**Amount**	**Unit**
Energy	Electricity	8.73E-02	kg	CPO	1.00E+00	kg
	Fuel	1.59E-04	kg	Shell	1.50E+00	kg
Material	Steam	2.74E-03	kg	Fibre	9.91E-01	kg
	Raw water	5.41E-03	kg	Kernel	2.50E-01	kg
	Fresh Fruit Bunch	4.95E+00	kg	POME	2.24E+00	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

The impact assessment uses openLCA software to create a flow based on inventory data. The type of flow generated in the software includes elementary, product, and waste flows, with a reference flow that is adjusted to each flow type. Existing flows are sorted and categorized into each unit process according to the system boundary of the LCA study used to visualize the entire process into a product system flowchart. The system product on the LCA CPO study is made with a reference flow which is the main product in this case is CPO with a total product of 134,794,850 kg/year. The product system is designed to enhance clarity and understanding of the actual CPO production process in the industry.

3.2. Impact Assessment Analysis

The assessment involved characterization, a stage aimed at identifying and classifying factors influencing impact across six impact categories, utilizing respective impact calculation methods. This impact assessment was conducted using openLCA software, employing the CML-IA Baseline and ReCiPe 2016 Midpoint (H) methods. Results of the environmental impact assessment are served in Table 3 and Figure 3.

Table 3. Impact assessment of crude palm oil production

No	Impact Category	Impact (based on process)		Total Impact (impact/kg CPO/year)	Reference Unit	Impact Calculation Method
		Upstream Process	Core Process			
1	Global Warming Potential (GWP)	3.98E-01	4.75E-01	8.74E-01	kg CO_2 eq	CML-IA Baseline
2	Acidification Potential (AP)	9.55E-04	1.55E-03	2.50E-03	kg SO_2 eq	CML-IA Baseline
3	Terrestrial Ecotoxicity Potential (TEP)	9.57E-01	4.33E+00	5.29E+00	kg 1.4-DCB	ReCiPe 2016 Midpoint (H)
4	Freshwater Ecotoxicity Potential (FEP)	9.44E-03	7.32E-03	1.68E-02	kg 1.4-DCB	ReCiPe 2016 Midpoint (H)
5	Human Toxicity Potential (HTP)	1.71E-01	1.19E-01	2.90E-01	kg 1.4-DB eq	CML-IA Baseline
6	Land Use Change (LUC)	6.72E-01	1.04E-02	6.83E-01	m^2a	ReCiPe 2016 Midpoint (H)

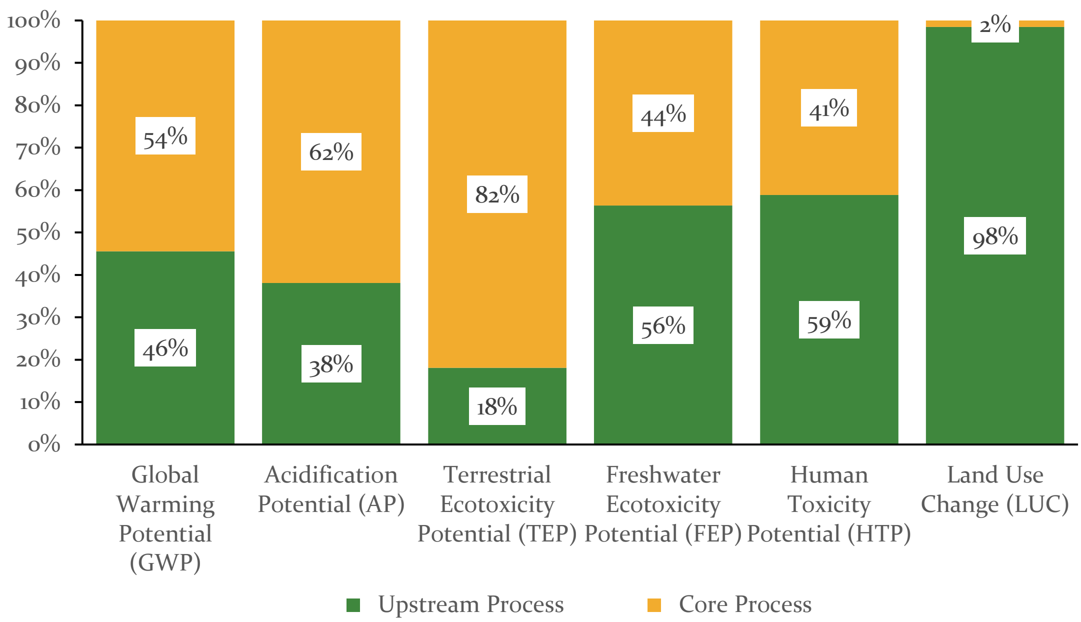

Figure 2. Distribution of emission in the upstream-core process of CPO Production

From Table 3, it can be inferred that the upstream process significantly affected freshwater ecotoxicity potential (FEP), human toxicity potential (HTP), and land use change (LUC). The upstream process involves oil palm nursery and maintenance activities, including seed fertilization, watering, pest, and disease control, followed by harvesting and transportation to palm oil mills. These activities require chemicals, such as fertilizers and pesticides, which necessitate chemical production processes. Production and chemical use produce emissions that have an impact on the FEP and HTP. Additionally, land clearing for oil palm nurseries and maintenance contributes to the LUC impact category. According to Maisarah and Rahmad (2023), the planting process in oil palm plantations accounts for a significant 23.2% of the overall LUC impact.

Conversely, the core process notably impacts global warming potential (GWP), acidification potential (AP), and terrestrial ecotoxicity potential (TEP) categories. Transportation of primary and utility materials and boiler units in the core process emit air pollutants such as SO_2, NO_2, CO, CH_4, N_2O, and CO_2 impacting GWP, AP, and TEP categories. In this study, transportation to the core process significantly contributes to GWP, AP, and TEP impacts due to fossil fuel usage and gradual activity, leading to substantial fuel consumption and environmental impacts. GWP reflects the environmental impact of fossil fuel combustion, releasing greenhouse gas emissions into the air, and causing global warming. results from volcanic eruptions and human activities like fossil fuel combustion (Futari, 2023). This aligns with the study by Brilianty et al. (2022), which indicated that transportation activities have the highest GWP and AP impacts at 7,298 kg CO_2eq and 2.132E-2 kg SO_2eq, respectively, compared to the overall process activities. LCA calculations conducted by Rinaldo and Suprihatin (2023) showed that producing 1 t of CPO requires 5 t of Fresh Fruit Bunches (FFB) and produces a GWP of 453 kgCO_2eq/tonne of CPO and Acidification of 1.51 kgSO_2eq/tonne of CPO.

3.3. Oil Extraction Rate Scenario

According to the environmental impact results that emerge as a result of the CPO production process, it is encouraged to explore the possibility of improvements that can be implemented to reduce the impact but not disrupt the operational activities of the palm oil industry. Careful consideration is needed to identify environmental improvements because the Indonesian economy aspect largely depends on the crude palm oil industry. The goal of these improvements is to support long-term, sustainable economic growth.

In this study, an analysis of potential improvements was conducted by optimizing the efforts for process mill activities. The mill process is the core or main process of CPO production, which occurs during the extraction of fresh fruit bunches (FFB) into CPO. The activities carried out in the milling process directly affect the output of the final product. Improvements are focused on the mill process first to enhance efficiency and increase productivity so that it is expected to create a positive domino effect throughout the crude palm oil lifecycle production. This research analyzed environmental improvements through optimizing the oil extraction rate (OER). OER is an important indicator in the palm oil industry. OER is the amount of oil obtained from fresh fruit bunches (FFB) (Hudori, 2023). A higher OER shows a mill's ability to produce more oil from each ton of Fresh Fruit Bunches (FFB) processed (Chew, 2022). However, it should be noted that FFB quality plays an important role in this process. Mature fruits have a higher oil content, so ensuring good quality FFB is a key factor in improving oil extraction yields (Azmi et al., 2022).

The OER value is closely related to the total FFB processed at the mill as well as the total oil produced. Current conditions show that the total FFB obtained was 66,7675,000 kg and produced a total CPO of 134,794,850 kg (based on Table 2) with an OER value of 20.19%. This OER is not much different from the OER value used by the crude palm oil industry in Malaysia, that is with the range OER of 19.64%-20,19% (MPOB, 2023). Sustainability improvement based on Oil Extraction Rate (OER) has attracted attention from researchers in the palm oil industry, especially when Malaysia set a target to achieve an OER of 23% by 2020. This focus is driven by based on the world's production of palm oil in 2018, approximately 3 million tons of additional palm oil can be produced globally by a 1% increase in OER (Chew, 2021).

According to Chew (2021), an effective way to improve milling efficiency is to use methods that increase oil extraction or minimize oil loss. Increased oil extraction can be achieved through various techniques, such as sterilization of fresh fruits or enzymatic methods in which the enzymes loosen the hemicellulose in the oil-containing cell wall, thus easing the release of oil during pressing. In addition, a method with the MICRONES (Maceration Induced Cell Rupturing Oil Nut Extraction Synthesis) system has recently emerged, which is a more efficient method of extracting coconut oil, with a lower rate of oil loss during the extraction process. The MICRONES method can increase the OER to 0.5% - 0.7% by removing the beans from the mesocarp and extracting the oil directly from the nuts-free mesocarp.

To find out the potential for the efficiency improvement of crude palm oil production, an analysis of the estimated increase in CPO product amount based on OER was carried out using the following equation (1) (Mielke, 2019).

$$Oil\ Extraction\ Rate\ (\%) = \frac{Total\ Oil\ Produced}{Total\ Fresh\ Bunches\ Processed}\ x\ 100\% \tag{1}$$

The total of fresh bunches processed in the calculation as a fixed variable that has the same value in each scenario. Then, the estimates of changes in the total oil produced with different OER options are with three scenarios with OER normal condition (20.19%), OER increased at 21% and 22%. In the calculation of these estimates, it was found that the OER increase was positively correlated with the total production of CPO (Figure 4). By increasing the extraction rate, it is possible to optimize the production of oil from fresh fruit bunches. The CPO production capacity can also be increased to compensate for the impacts of the production process. The higher the main product, the greater the divider for the impact category, which can reduce the impact value for each impact category.

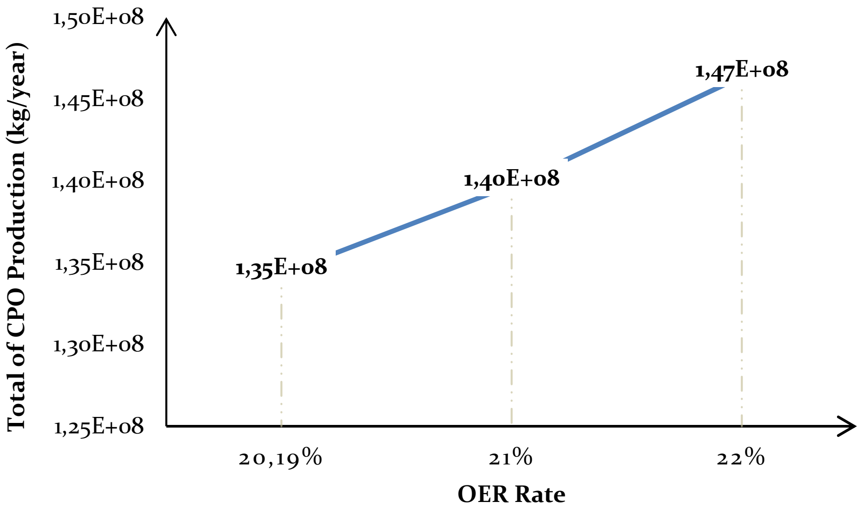

Figure 3. Total of CPO production estimated by OER Scenario

To support this potential improvement, the study also analyzes the possible environmental impact of the scenario of an increase in OER to CPO production. In this analysis, a comparison is made between the environmental impact that may be produced when OER is increased, with the value of environmental effects in current conditions that have been calculated previously. In this case, the impact value on OER of 20.19% is the baseline in the calculation of this comparison, and the impact category analyzed is the same as that of the baseline.

Table 4. Environmental performance changes of the increased OER scenario

Impact Category	Reference Unit	Environmental Impact Result			Percent Impact Reduction	
		Normal OER (OER 20.19%)	OER 21%	OER 22%	OER 21%	OER 22%
Global Warming Potential (GWP)	kg CO_2 eq	8.74E-01	8.40E-01	8.02E-01	3.86%	8.23%
Acidification Potential (AP)	kg SO_2 eq	2.50E-03	2.41E-03	2.30E-03	3.60%	8.00%
Terrestrial Ecotoxicity Potential (TEP)	kg 1.4-DCB	5.29E+00	5.08E+00	4.85E+00	3.88%	8.23%
Freshwater Ecotoxicity Potential (FEP)	kg 1.4-DCB	1.68E-02	1.61E-02	1.54E-02	3.88%	8.23%
Human Toxicity Potential (HTP)	kg 1.4-DB eq	2.90E-01	2.79E-01	2.66E-01	3.85%	8.23%
Land Use Change (LUC)	m^2a	6.83E-01	6.56E-01	6.27E-01	3.88%	8.23%

Based on Table 4, it can be seen that the scenario of increasing OER significantly has a positive effect on all environmental impact categories. The GWP, AP, and TEP impact, which is the dominant impact that exists and is contributed by the core production process of CPO, has decreased with the increase in OER. The percentage values of decrease are almost the same: at OER 21% GWP decreases 3.86%, AP decreases 3.60%, and TPE decreases 3.88%. Meanwhile, at OER 22%, GWP decreases by 8.23%, AP decreases by 8.00% and TEP decreases by 8.23%.

According to Figure 3, there is a positive correlation between the increase in CPO productivity from FFB and the scenario of increasing OER. An increase in the OER has the concept of producing more CPO from the same FFB. However, if examined more deeply in practice, there is a negative correlation between an increase in CPO productivity and demand for FFB. Industry players do not need to face the demand for more FFB to produce more CPO; with this OER scenario, the same amount of FFB can produce more CPO because the extraction process is more effective in producing oil, and the oil loss remaining in the empty bunches can be minimized (Ng et al., 2020).

In addition, Figure 3 shows that there is a positive correlation between the increase in CPO productivity from FFB and the increase in OER. Related to this concept, the CPO industry can optimize extraction with OER to produce more CPO when the demand for CPO increases. In such a situation, the possibility of land expansion to achieve CPO supply targets can be reduced. Indirect land use, deforestation, and greenhouse impacts can be reduced by the OER scenario. Higher CPO production reduces FFB demand and prevents oil palm plantations from expanding so that the potential for deforestation and greenhouse gas emissions can also be reduced (Khatiwada et al., 2021). This improvement scenario based on increasing OER has great potential to reduce the overall impact. As the total CPO product divisor increases, the increase in mill productivity in CPO production can lead to lower impact values for all impact categories tested, as shown in Table 5, which presents the impact analysis results after the improvement scenario with OER.

In this case, increased OER can drive oil production activities to become more efficient and the materials consumption portion both chemicals and other materials used in the production of CPOs can be reduced (Noranai, 2021). This has an impact on the reduction in the amount of greenhouse gas emissions and waste removed from the core process, the GWP impact can decrease as GRK emissions decline. The AP impact due to emissions of chemical compounds contained in waste effluent is also reduced so that potential changes in environmental acidity levels can be suppressed as well. Decreased waste concentration also reduces the potential for waste released into the soil which can cause soil pollution, so that the impact of TEP can be minimized.

The analysis of increasing OER in the crude palm oil industry has been proven to have a significant positive impact on overall sustainability, specifically in terms of reducing environmental impacts identified through LCA study. It is important to highlight that this research only examined environmental performance and did not include economic or social analyses. To improve the quality of future research, a multidisciplinary analysis that covers environmental, economic, and social aspects is recommended. This will provide a more holistic understanding of the implications of OER improvements in the palm oil industry and allow for more sustainable and efficient decision-making in the future. By reducing the environmental impacts of CPO production, the industry can move in a more sustainable direction, preserving natural resources and the environment while meeting the global demand for palm oil products.

4. Conclusions

The research conducted to analyze the environmental impact of CPO production was carried out using the LCA approach with the scope of a cradle-to-gate analysis scheme was carried out to evaluate the impact of the entire life cycle CPO production and the potential environmental performance in the improvement scenario based on OER increases. The Life Cycle Impact Assessment showed that CPO production had a significant impact on GWP of 8.74E-01 kg CO2eq, Terrestrial Eco-toxicity of 5.29E+00 kg 1,4-DCB, and Land Use Change of 6.83E-01 m2a. The composition of GWP Impact is 54% of emissions generated by core processes and 46% from upstream. For TEP, 82% of emissions come from the core process and 18% come from the upstream process, while for land use change, 2% from the core process and 98% from the upstream process. The scenario of OER increase as a step in improving the sustainability of the palm oil industry shows significant results in reducing all the impact categories calculated on the analysis of CPO production. OER increase of 21% can decrease all impacts by around 3% and a decrease of around 8% impact at an increase in OER of 22%. Oil extraction efficiency improvement that is consistent with sustainability principles also affects economic and social aspects. It is necessary to carry out further research that expands understanding of the implications and application of a more comprehensive approach to sustainability analysis that includes detailed economic and social aspects of optimizing OER in the palm oil industry, thereby enabling the industry to develop a more holistic strategy to achieve sustainable development in the future.

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