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Life Cycle Assessment (LCA) of Palm Oil Boiler Ash (POBA) Implementation Scenarios as an NPK Fertilizer Alternative Substitution in Palm Oil Plantations

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ABSTRACT
Indonesia is the world's largest producer of CPO, with high demand to meet global vegetable oil needs. To maintain the plantation productivity, NPK fertilizer provides additional nutrients. However, their intensive use has negative impacts on the environment, including causing imbalances in aquatic ecosystems due to agricultural run-off that promotes eutrophication and ecotoxicity. In addition, Palm Oil Boiler Ash (POBA) is a waste generated from CPO mill boilers, which is generally underutilized. Nevertheless, POBA has the potential to improve soil quality, although improper management may cause a pH imbalance in water bodies. This study modeled the POBA implementation as an alternative to NPK fertilizer with a Life Cycle Assessment (LCA) approach to evaluate the potential for reducing environmental impacts. The scenarios consisted of 0% or operational conditions, 10%, 30%, and 50% substitution of NPK fertilizer with POBA. openLCA 2.5.0 was used for impact calculation, supported by primary data, and secondary data from the Ecoinvent database 3.11. The results indicated a significant reduction in impact values, particularly in the eutrophication and ecotoxicity categories, with increasing proportions of POBA substitution. This modeling provides the palm oil industry with environmental improvement programs aimed at mitigating impacts and achieving sustainability goals.

1. INTRODUCTION

The palm oil industry plays a vital role in the Indonesian economy, and demand for Crude Palm Oil (CPO) as a key commodity is growing. Indonesia is a major CPO exporter, meeting global vegetable oil needs in 18 countries across Asia, Africa, and Europe. The growing demand for CPO is evident in the increase in oil palm plantation areas, approximately 32% in 2014 to 2024 (Statistics Indonesia, 2025). To obtain a high-quality fruit, oil palm cultivation practices generally depend on inorganic NPK (Nitrogen, Phosphorus, Potassium) fertilizers (Sigalingging et al, 2024). The plant uses nitrogen to form chlorophyll cells and promote leaf growth. Phosphorus is used to synthesize nucleic acids, which are subsequently utilized as cell builders, such as root formation and fruit ripening. Furthermore, potassium functions as an enzyme activator for plant metabolism and maintains plant productivity (Islam et al., 2025). Despite its effective results, the utilization of NPK fertilizers can have negative impacts on soil health, such as soil degradation, disrupting soil microbial stability, and causing the soil to be unable to absorb water, resulting in a decrease in soil pH (Azahari & Sukarman, 2023). In addition, NPK fertilizers also impact the water bodies by increasing the potential for eutrophication and disrupting the aquatic organisms (Semenov et al., 2023; Helen et al., 2020).

In the CPO production process, shells and fibers are generated as waste and are usually used as fuel in boilers to generate energy. The combustion results in boiler ash, commonly known as Palm Oil Boiler Ash (POBA). The challenge that CPO mills encounter is the large amount of POBA, which requires further treatment because it has a detrimental impact on the environment if stockpiled. Its impact is disrupting the stability of pH in water bodies, due to runoff water exposed to POBA (Skoronski et al., 2017). Nevertheless, POBA is reported consisting nutrients such as potassium (K) in the range of 0.8-22%, calcium (Ca) 0.8-38%, magnesium (Mg) 0.4-4%, phosphorus (P) 0.2-4%, nitrogen (N) 0.1-0.7%, and silica (Si) in the range of 0.3-3% (Rosyidi et al., 2022); (Sopa., 2021); (Tarigan et al., 2024); (Veranika et al., 2018).

These mineral contents act to form soil aggregates, making them more stable and increasing porosity, which enforces water infiltration and soil aeration (Thaharah et al., 2024; Huang et al., 2019). Hence, POBA has the potential to be utilized as an agent to improve degraded land and improve soil quality in oil palm plantations. POBA has an alkaline pH, and it can be deployed to manage acidic soils (Ermadani et al., 2024); (Ichriani et al., 2021). Based on its content, POBA has the potential to be further utilized as an alternative to chemical fertilizers, as well as reduce the costs of handling POBA waste. Utilization of POBA as an alternative substitute for inorganic fertilizers.

Life Cycle Assessment (LCA) is an analytical method used to determine the environmental impact of a product, process, or service. Furthermore, LCA can be used to determine whether the utilization of POBA can reduce the environmental impact of inorganic fertilizer usage in oil palm plantations. This study aims to evaluate POBA implementation scenarios as an alternative to chemical fertilizers in oil palm plantations using the LCA method, which supports the circular economy concept and represents an environmental improvement program.

2. METHOD

This study employed the LCA method to evaluate the POBA implementation scenarios as an alternative chemical fertilizer in an oil palm plantation area. The stages of the LCA were based on the reference standards SNI ISO 14040:2016 and SNI ISO 14044:2017, beginning with goal and scope, followed by life cycle inventory, life cycle impact assessment, and interpretation. This methodology was used to ensure consistency, transparency, and comparability of the analysis results across the evaluated scenarios.

2.1 Goal and Scope

The objective of this study is to determine the environmental impact of the operational process of the CPO mill that uses NPK fertilizer in oil palm plantations, and compare these impacts with the POBA implementation scenarios as an alternative to NPK fertilizer. The scope follows a cradle-to-gate approach, encompassing the upstream process of oil palm cultivation and the core process, including CPO production. The study refers to the Product Category Rules (PCR) for Basic Chemicals, UN CPC 341, 342, and 345 (excluding subclass 3451), Version 1.1.5 (2021). All calculations are carried out based on a declaration unit of 1 kg of CPO produced. The system boundary of this study is represented in Figure 1.

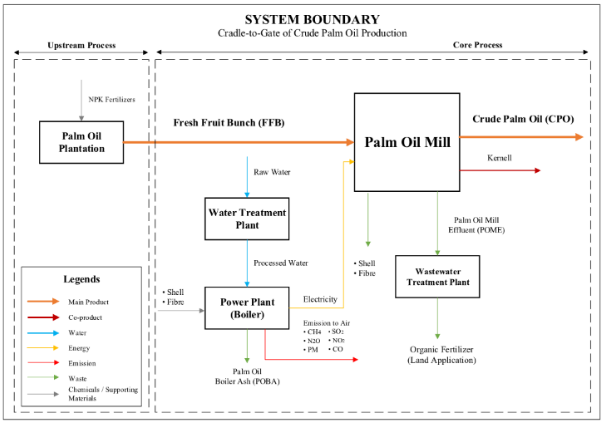

Figure 1. System Boundary

2.2 Life Cycle Inventory

This crucial stage involved data collection, processing, and creating inventory data. The data covered the 2024-2025 period and included inputs such as energy, water, raw and supporting materials, as well as outputs including main products, co-products, and emissions from the production system. The LCI was based on primary data through site visits, interviews, laboratory analysis, and emission calculations, complemented by secondary data from the Ecoinvent v.311 database and relevant literature.

Table 1. Data Inventory Cradle-to-Gate CPO Production

Flow Type	Category	Flow	Amount	Unit
		Upstream		
Input	Energy	Fuel	1,15E-01	kg
	Fertilizer	NPK Fertilizer	3,54E+06	kg
Output	Product	Fresh Fruit Bunch	3,33E+08	kg
		Core		
Input	Raw Material	Fresh Fruit Bunch	4,35E+00	kg
	Other Material	Raw water	3,48E+00	kg
	Energy for Power Plant	Fuel - Solar	1,33E-03	kg
		Shell	2,24E-01	kg
		Fibre	4,55E-01	kg
		Steam	2,27E+00	kg
	Energy for Process	Electricity	9,50E-02	kg
Output	Main Product	CPO	1,00E+00	kg
	Co-product	Kernel	1,93E-01	kg
	Waste	Palm Oil Boiler Ash (POBA)	1,78E-02	kg
	Emission from Power Plant (Boiler)	CH_4	2,24E-01	kg
		N_2O	4,55E-01	kg
		NO_2	2,64E+00	kg
		CO	9,50E-02	kg

Flow Type	Category	Flow	Amount	Unit
	Other	Particulate	4,75E-02	kg
		SO_2	2,67E-04	kg
		Shell for Power Plant	5,61E-04	kg
		Fibre for Power Plant	1,30E-04	kg
		POME for Organic Fertilizer	5,90E-05	kg

Source: Internal Company Data (2025)

2.3 Life Cycle Impact Assessment (LCIA)

LCIA aimed to evaluate potential environmental impacts based on inventory data modeled in the LCI stage. In this study, data analysis was conducted using openLCA version 2.5.0 and the Cut-off LCI system model. The environmental impact assessment focused on impact categories directly related to the implementation of POBA, such as Marine Aquatic Ecotoxicity Potential (MAEP), Freshwater Ecotoxicity Potential (FEP), Terrestrial Ecotoxicity Potential (TEP), Freshwater Eutrophication Potential (FEuP), Marine Eutrophication Potential (MEuP), and Global Warming Potential (GWP). Impact calculations were performed using the ReCiPe Midpoint H 2016. The calculation method is selected due to its comprehensive coverage of impact categories regarding ecotoxicity and eutrophication.

2.4 POBA Implementation Scenarios

This study conducted an impact analysis on four POBA implementation scenarios as an alternative to NPK fertilizers in palm plantations to evaluate their potential for reducing environmental impacts. Scenario 1 represented the operational condition in which NPK fertilizers were applied at 100% in the plantation, and the POBA generated as residue from biomass combustion was not utilized as an alternative. In scenarios 2 to 4, POBA was modeled as a partial substitute for NPK fertilizer at concentrations of 10%, 30%, and 50% as shown in Figure 2. These scenarios will be compared with scenario 1 to determine the potential reduction in environmental impacts, which are discussed in the following section.

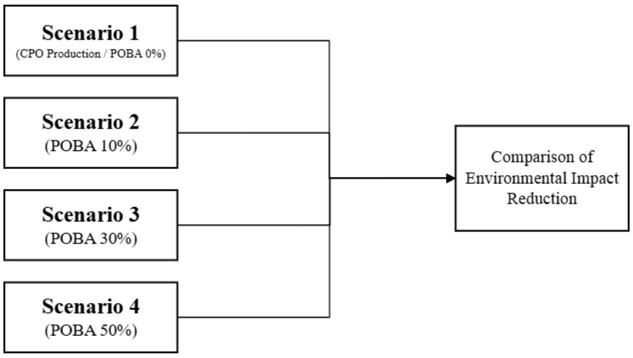

Figure 2. Schematic Design

3. RESULTS AND DISCUSSION

In this section, the environmental impacts of CPO production using 100% NPK fertilizer on the plantation are discussed and compared with substituting POBA for NPK at various concentrations. The results showed a decrease in impact values due to the reduced use of NPK fertilizer, which impacts the predetermined impact categories.

3.1 Environmental Impacts of CPO Production under Operational Condition

The operational conditions on a palm oil plantation using NPK fertilizer are represented in scenario 1. In this scenario, the POBA has not been utilized as an alternative fertilizer on the plantation. The LCIA results for this scenario are shown in Table 2 and act as a baseline for comparison to evaluate the environmental performance of the POBA implementation scenario implemented.

Table 2. Environmental Impact Result of Scenario 1

Impact Category	Impact Result	Reference Unit
FEP	2,13E-02	kg 1,4-DCB-eq
TEP	1,38E+00	kg 1,4-DCB-eq
MAEP	2,83E-02	kg 1,4-DCB-eq
GWP	8,37E+00	kg CO_2 eq
FEuP	7,31E-05	kg P eq
MEuP	4,29E-05	kg N eq

Source: Internal Company Data (2025)

Based on Figure 3, the production and use of NPK fertilizers are the main hotspot, which influences the impact result of several impact categories, including GWP, FEuP, and MEuP, as well as ecotoxicity categories such as MAEP, FEP, and TEP. Moreover, fertilizer transportation from the supplier to the plantation also contributes to several impact categories, particularly those related to GHG emissions and the use of fossil fuels during transportation. The intensive energy use in the NPK production process contributed significantly to the GWP value. Furthermore, N_2O emissions generated from nitrogen fertilizer application in plantations had a global warming potential 273 times greater than that of CO_2 (IPCC, 2021). The use of nitrogen fertilizers biogeochemically stimulates nitrification and denitrification processes in the soil, which produce N_2O as a byproduct (Simplicio et al., 2016).

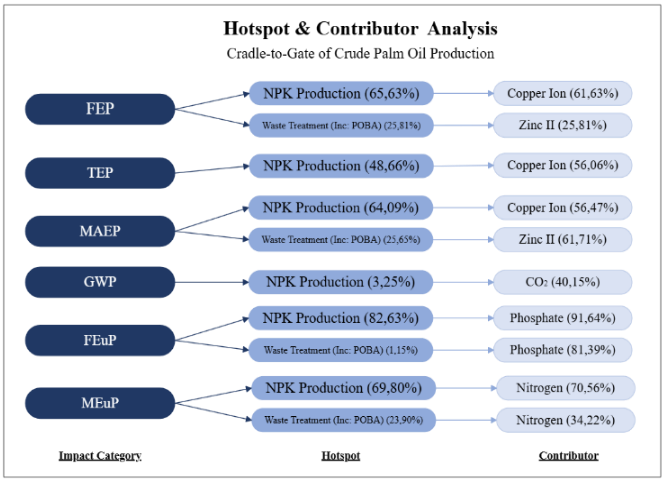

Figure 3. Hotspot and Contributor Analysis of Scenario 1

Meanwhile, increasing eutrophication value is related to the runoff and leaching of nitrogen and phosphorus elements from NPK fertilizers into water bodies. It contributes to the nutrients' accumulation found in water bodies, which subsequently stimulates the dense aquatic plants (Akinnawo, 2023). Shukla et al. (2022) reported that an imbalance of NPK fertilizer usage exacerbates water quality and increases the risk of eutrophication. Emissions and metal content from fertilizer production and transportation are crucial factors for ecotoxicity impact categories. It aligns with Mankong et al. (2024), which showed that fertilizer usage and nutrient management in crop cultivation systems contribute to the ecotoxicity category in life cycle analysis. Furthermore, inorganic fertilizers have also been reported as a source of anthropogenic heavy metals, such as Cu and Zn, in agroecosystems, which potentially affect the toxicity of aquatic and terrestrial organisms (Alengebawy et al., 2021).

Likewise, POBA is also identified in the inventory as a waste flow included in the waste management process and contributes to the impact category, albeit at a relatively small value. Waste flow allocated to disposal is modeled as process units with quantified emission potential, and it is emphasized that expanding the analysis to various types of waste is important for a more comprehensive sustainability evaluation (Nurzhan et al., 2025). Ouedraogo et al. (2024) explained that end-of-life waste treatment, including landfilling, composting, incineration, gasification, and anaerobic digestion, systematically affects ecotoxicity and eutrophication impact categories. Although the impact contribution of POBA is relatively small compared to NPK fertilizer production, it imposes quantified environmental impacts.

3.2 Environmental Performance of POBA Implementation Scenarios

Scenarios 2, 3, and 4 were modeled to evaluate the POBA implementation as a substitute for NPK fertilizers for reducing environmental impacts, which are illustrated in Table 3. In these models, the total nutrient requirements of palm oil plants were assumed to be constant; thus, the rise of POBA percentage directly correlated with a proportional reduction in NPK fertilizer usage.

Table 3. POBA Implentation Scenarios Result

Impact Category	Percent Impact Reduction		
	Scenario 2 (10% POBA)	Scenario 3 (30% POBA)	Scenario 4 (50% POBA)
FEP	3,04%	9,11%	15,18%
TEP	0,38%	1,13%	1,89%
MAEP	3,01%	9,02%	15,04%
GWP	0,04%	0,12%	0,19%
FEuP	0,75%	2,26%	3,76%
MEuP	2,88%	8,64%	14,40%

Source: Internal Company Data (2025)

The LCIA results for scenarios 2, 3, and 4 show a steady decline in environmental impacts as the proportion of POBA substitution increases, with the most significant reduction in scenario 4. It occurred in the FEP, MAEP, and MEuP categories, followed by FEuP, TEP, and GWP, respectively. This indicates that POBA substitution affects impact categories that are sensitive to dissolved metals derived from fertilizers and the POBA processing process. Interestingly, the FEP, MAEP, and MEuP categories were reduced due to the POBA implementation.

The reduction in FEP and MAEP values is correlated with the reduction in the flow of copper (Cu^{2+}) and zinc (Zn^{2+}) ions from the open dumping disposal process. Zn is relatively reactive and readily oxidized under favorable conditions, while Cu can be distributed in various mineral phases, making both elements susceptible to release into the environment through toxic leaching (Scholz et al., 2024). By maximizing the potential of POBA, excessive metal emissions from the disposal treatment can be significantly lowered. The amount of bound nitrogen released to the ocean from waste treatment influenced the MEuP value. Nitrogen is a contributor that induces the potential for eutrophication and promotes massive algae blooms in the sea (Mendrofa, 2025).

The impact reductions in the FEuP, TEP, and GWP categories are indirectly driven by decreased NPK fertilizer use following its substitution with POBA. Phosphate (PO_4^{3-}), found in NPK fertilizer components, is a nutrient that can boost freshwater eutrophication and affects FEuP values (Golubkov & Golubkov, 2025). In addition, reduced copper (Cu^{2+}) from NPK fertilizer production contribute to the decline in TEP values. Meanwhile, the substitution of NPK with POBA also lowers CO_2 emission for the GWP category.

Furthermore, freshwater and marine eutrophication also pose risks to human health. Indirect effects include the consumption of water from polluted water bodies by algae blooms, leading to gastrointestinal problems due to the secretions of blue-green algae. In addition, skin and respiratory problems are categorized as direct effects, caused by inhaling evaporation from eutrophic waters (Zhidkova et al., 2020). Similar to eutrophication, ecotoxicity also has a negative impact on human health. Toxins found in aquatic organisms accumulate in the human bodies that consume them. Consequently, chronic diseases such as neurological problems, kidney failure, cardiovascular disease, and even cancer can occur due to long-term exposure to heavy metals (Azar & Vajarga, 2023).

3.3 Limitations and Future Research

This study has several limitations, such as the area of palm oil mills and plantations located in Kalimantan. Thus, the geographic representativeness is limited, nationally and globally. Furthermore, there were differences in soil characteristics, agroclimatic conditions, rainfall intensity, and plantation management practices. Variations in the characteristics of POBA produced by each palm oil mill potentially influence nutrient content and the effectiveness of NPK fertilizer substitution. In relation to data sources, this study utilized not only primary data but also secondary data, such as NPK fertilizer production from the Ecoinvent 3.11 database. This dataset represents general fertilizer production conditions and does not fully describe the characteristics of the NPK fertilizer production system in Indonesia. Furthermore, the study utilized scenario-based modeling in calculation software, which did not include field validation or long-term monitoring of the effects of POBA application on soil quality, nutrient dynamics, and crop productivity.

Further research may include analyzing the physicochemical characteristics and nutrient content variability of POBA from various mills and production areas, considering that differences in biomass types and boiler operating conditions can potentially affect POBA quality. Long-term field validation is also necessary to assess agronomic performance, changes in soil quality, nutrient dynamics, and the environmental implications of POBA application as a partial substitute for NPK fertilizers. Furthermore, further research should focus on determining the optimal substitution dose and developing a more data-driven inventory to improve data traceability and the accuracy of LCA results in the Indonesian palm oil sector. This further research could validate the assumptions and scenarios in this LCA study, making it more representative and reliable.

4. CONCLUSION

In summary, the environmental impact reduction was achieved through two approaches: decreasing the use of NPK fertilizer and utilizing POBA waste as a substitute for NPK fertilizer. At once, the modeled scenario illustrates that both the environmental impact in the upstream and downstream show consistent reduction in scenarios 2 to 4. This implies that waste-to-fertilizer efforts show potential as an environmental improvement program to achieve sustainability goals in the palm oil industry.

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