



Potential environmental impact of biodiesel production from palm oil using LCA (Life Cycle Assessment) in Indonesia

Ari Kabul Paminto^{ab}, Mahawan Karuniasa^a, Evi Frimawaty^a

^a School of Environmental Science, Universitas Indonesia, Kampus Salemba, 10430, Indonesia [+62 21-31930251]

^b Research Center for Industry Process, National Research and Innovation Agency (BRIN), Tangerang Selatan, 15314, Indonesia

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Corresponding Author:

Ari Kabul Paminto

School of Environmental

Science, Universitas Indonesia;

Tel. +6281219354779

Email:

ari.k.paminto@gmail.com

Abstract. *Indonesia produced 1 504 million BOE (Barrel of Oil Equivalent) of primary energy in 2018, consisting of the petroleum, natural gas, coal, and renewable energy. The reliance on fuel oil, particularly in the transportation industry, remains strong. The international commitment to decreasing greenhouse gas emissions compels the Indonesian government to promote new and renewable energy. The Life Cycle Assessment (LCA) technique has become increasingly popular for assessing the environmental effect, energy consumption, and GHG (Greenhouse Gas) emissions associated with biofuel production. Numerous phases must be addressed when determining the life cycle impact of biodiesel, including land-use change, plantation, milling, refining, and fuel conversion. Numerous research has been conducted on the life cycle of palm oil production. However, most of them continue to be concerned with GHG emissions and energy needs. As a result, this paper will give a life cycle assessment of biodiesel production in Indonesia from the plantation phase through the production phase using larger effect categories. According to the analysis, the primary contributors to the environmental impact of biodiesel production are fertilizer consumption during the plantation stage and the transesterification process at the biodiesel plant.*

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INTRODUCTION

Indonesia produced 1 504 million barrels of oil equivalent (BOE) of primary energy in 2018, including oil, natural gas, coal, and renewable energy (BPPT, 2020). Dependence on fuel oil consumption remains high, mainly in the transportation sector, as the dominance of fuel-based transportation technologies remains unaltered by electricity and natural gas-based transportation technologies. This situation increases the reliance on energy imports, as most of the fuel demand is met from imports. According to the RDMP (Refinery Development Master Plan) and GRR (Grassroots Refinery) programs, crude oil imports continue to grow as refineries develop, averaging 4.3% per year. In 2018, total energy consumption in Indonesia (without traditional biomass) was around 875 million BOE, with 40% for the transportation sector, 38% for industry, 15% for households, 5% for the commercial sector, and 2% for other sectors (BPPT, 2020; MEMR, 2019). Oil production in Indonesia in 2018 was 772 thousand boepd (barrels oil equivalent per day) or decreased by 29 thousand boepd from 2017 (SKK Migas, 2019).

The international commitment to reduce greenhouse gas emissions pushes the Indonesian government to embrace the role of new and renewable energy sources in ensuring the country's energy security and independence (DEN, 2019). Government Regulation No. 79 of 2014 on the National Energy Policy targets at least 23% new and renewable energy by 2025 and 31% by 2050. Renewable energy consumption in transportation, particularly biodiesel, is increasing quickly due to the mandatory B30 legislation enacted in early 2020. Vegetable oil can replace the same function of petroleum derivative products with the advantage of being more environmentally friendly and renewable (Ramdhani *et al.*, 2019). Biodiesel is a flammable liquid fuel that can be decomposed in a monoalkyl manner derived from vegetable oils. The core bases of biodiesel currently available are crops such as soybean (*Glycine max*), cottonseed (*Gossypium hirsutum*), jatropha (*Jatropha curcas*), and oil palm (*Elaeis guineensis*). Biodiesel production in Indonesia is mostly based on palm oil and can boost bioenergy development initiatives significantly (Wahyono *et al.*, 2020). In 2019, palm oil production reached 51.8 million tons, and about 5.8 million tons of CPO (Crude Palm Oil) were used for domestic biodiesel production (GAPKI, 2019). Indonesia is the world's biggest palm oil producer, accounting for half of the world's crude palm oil production (FAOStat, 2020). In Indonesia, the potential for palm oil as a food source and key raw material for biodiesel is also quite large (USDA, 2019).

Consideration of the environmental impact of producing palm oil into biodiesel has begun. LCA has become a prevalent method for assessing energy consumption and GHG emissions from biomass biofuel production. LCA includes a scheme for measuring a product system's inputs and outputs and its potential environmental impact on its life cycle. Various industries have used ISO 14040 and 14044 standard schemes to communicate the environmental performance of industrial products (ISO 2006a, 2006b). Focusing on the environmental impact of a product or service, the stages of assessment are raw materials, supply, product use, and final disposal. LCA is also useful for detecting emissions caused by land-use change. The results heavily depend on the dependability and adequacy of the data inventory of the subject being assessed, so data collection is critical. It should be the primary focus of LCA implementation because it is the most time-consuming process (Siregar *et al.*, 2020a).

Many stages must be considered when assessing the impact of biodiesel on the life cycle, including land-use change, plantation, milling, refining, and fuel switching (Maharjan *et al.*, 2017). Earlier LCA studies on palm oil biodiesel included single or partial stage considerations in the overall assessment (Achten *et al.*, 2010; Nazir and Setyaningsih, 2010; Sampattagul *et al.*, 2011; Vargas-Gómez, 2009; Yee *et al.*, 2009; Zutphen and Wijbrans, 2011). Previously, Yee *et al.* (2009) demonstrated that palm biodiesel had a net energy ratio of 3.53. Furthermore, burning palm oil biodiesel is more environmentally friendly, emitting 38% less CO₂ per liter than petroleum-derived diesel. According to Zutphen and Wijbrans (2011), palm oil-derived biodiesel's life cycle of greenhouse gas emissions was 1 601 kg CO₂ per ton of biodiesel (including the production and combustion stages), 2.6 times less than conventional diesel. Pleanjai and Gheewala (2009) determined that the palm methyl ester (PME) life cycle requires a net energy balance of 100.84 GJ/ha and a net energy ratio of 3.58 (Harsono *et al.*, 2012; Soraya *et al.*, 2014) studies to examine the possible influence of greenhouse gas emissions and global warming on the biodiesel production life cycle.

Carbon emissions from land-use change are a significant factor in the GHG emission intensity of palm oil-based biodiesel production, according to life-cycle studies (Harsono *et al.*, 2012; Hassan *et al.*, 2011; Rodrigues *et al.*, 2014; Schebek *et al.*, 2018; Siangjaeo *et al.*, 2011; Silalertruksa *et al.*, 2017; Souza *et al.*, 2012). Calculating nitrogen (N₂O, NO_x, and NH₃) and phosphorus emissions from oil palm plantations is critical for the LCA of palm oil-based biodiesel. This computation affects the outcomes of various environmental consequences, including greenhouse gas emissions, eutrophication, and acidification (Achten *et al.*, 2010; Choo *et al.*, 2011; Souza *et al.*, 2010; Harsono *et al.*, 2012; Reijnders and Huijbregts, 2011). Numerous research has already documented the palm oil production cycle. However, most life cycle evaluations continue to focus on greenhouse gas emissions and energy demand, while only a few consider broader environmental implications. Therefore, this paper will present LCA with a broader category of impacts from biodiesel production in Indonesia from the plantation phase to the production phase.

METHOD

Data Collection

Data on the production process of palm oil mills were collected from secondary data of palm oil mills in Aceh Province and supplemented by data from international journals (Siregar *et al.*, 2020b). The data of the biodiesel production process was collected from the biodiesel production secondary data of BTBRD (*Balai Teknologi Bahan Bakar dan Rekayasa Disain*)-BPPT, Indonesia (Siregar *et al.*, 2013; Siregar, 2014). The study and data collection period were from January 2021 to March 2021. The functional unit used in this study is 1 ton of palm oil biodiesel. The list includes all inputs and outputs at the boundaries of the biodiesel production system. Table 1 shows the inputs and outputs for each stage of biodiesel production. Per hectare of plantation used during the planting period, 4.99 tonnes of fresh fruit bunches were produced (Soraya *et al.*, 2014). On the other hand, there are several main products and by-products produced by palm oil mills. Its main product is crude palm oil, with an estimated 0.20 tons per ton of fresh fruit bunches processed. By-products were fiber and husks, empty fruit bunches, and Palm Oil Mill Effluent (POME), yielding 31.2 kg, 1.15 tonnes, and 2.99 m³, respectively (Siregar *et al.*, 2020a; Soraya *et al.*, 2014). For the transesterification process, the conversion efficiency of CPO to biodiesel is 99%, so the yield of palm biodiesel is calculated as 0.99 tons of biodiesel per ton of CPO feedstock.

Table 1 Inventory data for 1 ton of biodiesel production

Process		Input	Unit
Oil Palm Plantation Fresh Fruit Bunch 6.4 ton	Chemical	873	Kg
	Water	2 960	Liter
	Fuel	5.5	Liter
CPO Production 1.3 ton	Electricity	48	kWh
	Fuel	5.1	Liter
	Water	0.9	m ³
	Steam	65	Kg
	Chemical	31	Kg
Biodiesel Production 1 ton	Electricity	15.6	kWh
	Water	1 700	Liter
	Fuel	14	Liter
	Chemical	0.43	ton

(Source: Data processed from Siregar *et al.*, 2020b; Siregar, 2014)

Data Analysis

The analytical methodologies utilized in this study are ISO 14040:2006 and ISO 14044:2006 LCA methods for estimating the environmental effect of biodiesel made from palm oil. The life cycle assessment framework comprises four steps: objective and scope definition, inventory analysis, impact assessment, and interpretation (Figure 1). Open LCA 1.10 was utilized with the ReCIPE impact assessment approach. The primary purpose is to assess Indonesian-produced first-generation biodiesel (palm oil)'s environmental performance and identify significant environmental hotspots. The study's limitation is its cradle-to-gate approach, which begins with manufacturing the raw material (fresh fruit bunches) and ends with the creation of the biodiesel product. The life cycle of biodiesel manufacturing is comprised of three processing units: oil palm plantation for Fresh Fruit Bunches (FFB), palm oil production for CPO, and biodiesel synthesis (Harsono *et al.*, 2012; Siregar, 2014; Soraya *et al.*, 2014).

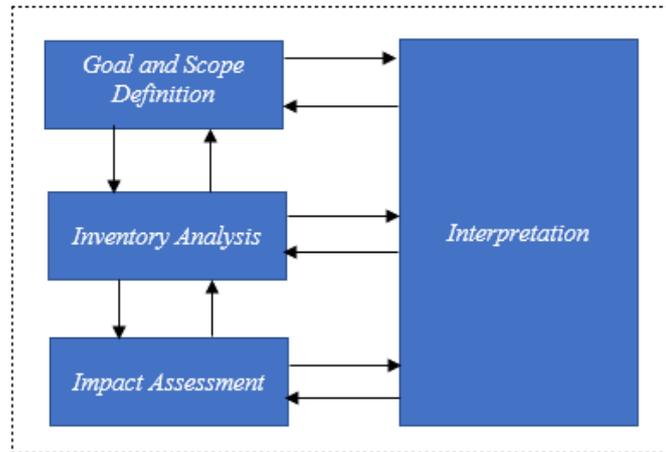


Figure 1 Stages of life cycle assessment analysis (ISO 14040: 2006)

RESULTS AND DISCUSSION

Global Warming Potential (GWP)

Figure 2 shows the GWP for each biodiesel production of the life cycle stage. The total GWP for 1 ton of biodiesel production is 2 762 kg CO₂-eq, of which 90% is from the planting stage, 1.1% is from the CPO production, and 8.8% of the biodiesel process stage. During the planting stage, nitrogen fertilizer emissions and land-use change contributed significantly, 29.8% and 23.2%, respectively. The contributions of K₂O and P₂O₅ fertilizers are relatively small compared to N fertilizers. In addition to fertilizers, plants also need pesticides and herbicides to grow properly. The application of pesticides contributed 0.15%, while the contribution of herbicides was almost negligible as it was less than 0.1%.

The palm oil production stage contributes around 1.1%, and biodiesel production accounts for 8.8% of GHG emissions. POME waste from palm oil will produce methane emissions to contribute to GHG emissions. Transportation has the second contribution after POME because FFB must be transported starting the plantation site to the mill. The relatively long vehicle mileage between the product collection points of each division to the PKS (Palm Oil Mill) and PKS to the port causes high diesel oil consumption (Dewani *et al.*, 2014). In biodiesel production, the transesterification stage provides the largest contribution, especially to using methanol as a supporting material, with 67% of GHG emissions.

Eutrophication

A pollution process occurs when a lake or river becomes too rich in plant nutrients; as a result, algae and other aquatic plants grow (Acero *et al.*, 2016). The total impact of eutrophication was 1.24 kg PO₄-eq, 67.6% of which came from the plantation stage (Figure 3). The main contributors of NO and NO₂ are released from fertilizer application during the plantation process. Eutrophication from the plantation process was 0.84 kg PO₄-eq and CPO production was 0.32 kg PO₄-eq.

Acidification

Compounds with acidification potential are those that are precursors to acid rain. Sulfur dioxide (SO₂), nitrogen oxides (NO_x), nitric oxide (NO), nitrogen dioxide (N₂O), and others are examples (Losacco and Perillo, 2018). Acidification potential is often characterized by SO₂ equivalents (Dincer and Abu-Rayash, 2020). The potential total acidification impact was 24.8 kg SO₂-eq, with the main contributor being the cultivation stage (Figure 4), which accounted for about 98%, followed by the biodiesel production stage, which was about 0.4 kg SO₂-eq. The plantation stage gives the highest contribution due to land-use change and extensive K₂O fertilizers.

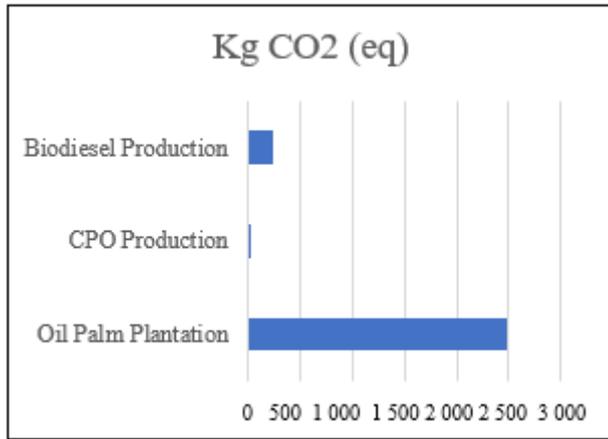


Figure 2 Global warming potential of the biodiesel process

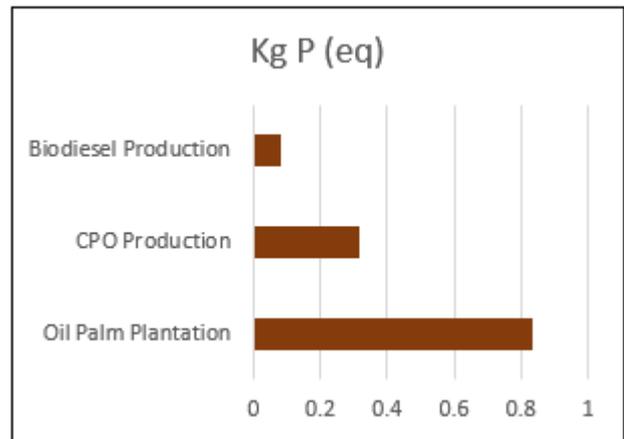


Figure 3 Eutrophication of the biodiesel process

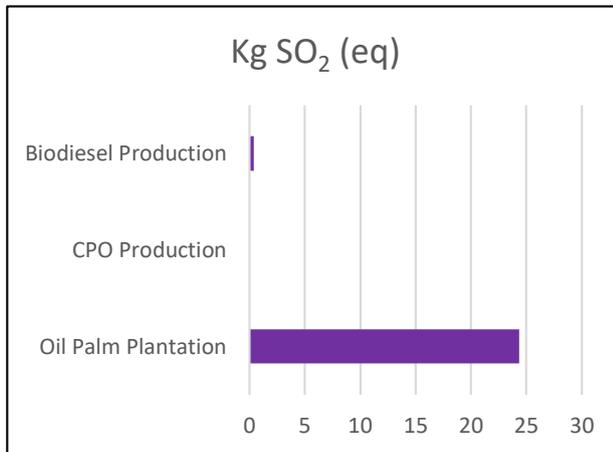


Figure 4 Acidification of the biodiesel process

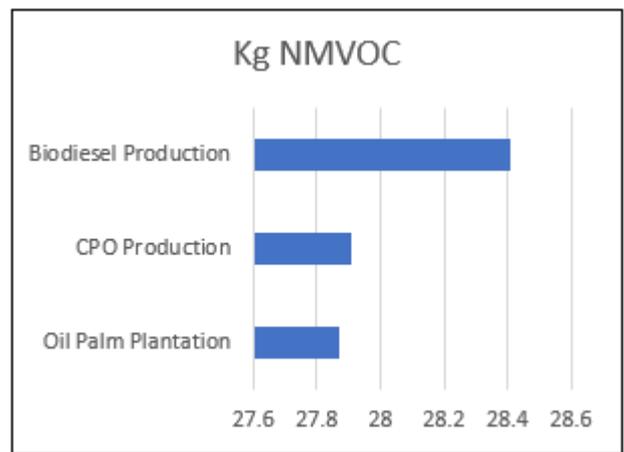


Figure 5 Photochemical oxidation of the biodiesel process

Photochemical Oxidation

Secondary air pollution, also known as summer smog, is caused by photochemical oxidation. It is formed in the troposphere primarily due to sunlight reacting with other chemical emissions from the combustion of fossil fuels (LCANZ, 2015). Figure 5 for photochemical oxidation shows that the biodiesel production stage is the largest contributor to this environmental impact, with about 28.4 kg NMVOC, followed by the CPO production process with about 27.9 kg NMVOC. This effect is caused by SO₂ and CO emissions from electricity use in palm oil mills and biodiesel pilot plants. Electricity used by the factory and pilot plant comes from Indonesia's power grid, which uses mostly coal as fuel. The total photochemical oxidation was 84.2 kg NMVOC.

Human Toxicity

Human toxicity potential is a calculated metric that reflects the potential hazard per unit of chemical released into the environment and is based on the characteristic toxicity of the compound and its potential dose (Acero *et al.*, 2016). These chemicals can be harmful to humans through inhalation, ingestion, and even exposure. For example, the possibility of cancer is an issue here. The potential total human toxicity effect is 5 291.7 Kg 1.4 DCB (eq), the main contributor is the CPO production stage (Figure 6), which accounts for about 74%, followed by the oil palm cultivation stage, which is 1 287.6 Kg 1.4 DCB (eq).

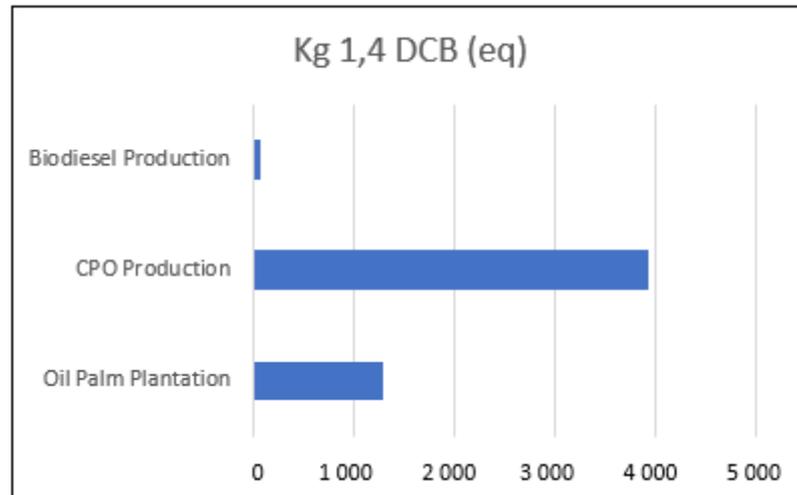


Figure 6 Human toxicity of the biodiesel process

CONCLUSION

The result of a complete analysis of the life cycle of biodiesel production from palm oil, starting from the oil palm cultivation stage, from plantation to factory, palm oil production stage, from factory transportation to biodiesel plant, and transesterification into FAME (Fatty Acid Methyl Ester) or biodiesel. The full analysis results can conclude that the main contributors to the environmental impact of biodiesel production are the use of fertilizers at the planting stage and the transesterification process in biodiesel plants. The environmental impact of the transport phase cannot be ignored, like all vehicles in this study run on diesel. The distance from plantations to palm oil mills and biodiesel plants needs to be considered because it will affect the number of emissions produced. In addition, emissions from the fuel can be reduced by improving the fuel production process and fuel quality. The transesterification process contributes to the environmental effects of biodiesel production due to the use of electricity and supporting material, namely methanol. Efficient use of methanol and electricity in biodiesel production units can reduce the resulting emissions. In addition, in terms of land-use change, efforts are needed to increase the yield of CPO per hectare (technology change) and take measures to protect peatlands, which leads to a decrease in the conversion of peat areas.

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