JEK
Journal of Earth Kingdom
JEK 2(2): 96–112
ISSN 3024-9821

Institute for Advanced Science,
Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Utilization of POME waste as a renewable energy source in the life cycle concept of palm oil biodiesel

Ari Kabul Paminto[1,2*]
[1] *Environmental Science Study Program, School of Environmental Science, Universitas Indonesia, Depok, Jawa Barat, 16424, Indonesia;*
[2] *Badan Riset dan Inovasi Nasional (BRIN), Tangerang Selatan, 15314, Indonesia.*
*Correspondence: arik002@brin.go.id

Received Date: December 4, 2024 Revised Date: January 15, 2025 Accepted Date: January 31, 2025

ABSTRACT

Background: In 2024, Indonesia, an importer of crude oil and fuel, is shifting focus to renewable energy as fossil fuel production declines. This research aims to develop a life cycle concept for biodiesel production from palm oil, addressing environmental concerns related to emissions from FFB, CPO, and biodiesel production processes. **Methods:** The method used in this research is a combination of quantitative LCA (Life Cycle Assessment) and AHP (Analytical Hierarchy Process) along with qualitative methods. **Findings:** This research identifies and evaluates the alternative utilization of Palm Oil Mill Effluent (POME) waste with certain priority weights. The results showed that biodiesel production from palm oil requires various significant inputs, such as NPK fertilizer, herbicides, water, diesel, and Crude Palm Oil (CPO), resulting in environmental emissions in the form of CO_2 of 1489 Kg CO_2 (eq) per ton of biodiesel, as well as contributions to eutrophication and acidification. The LCI (Life Cycle Inventory) analysis also identified that the largest CO_2 emissions came from POME waste (53%), followed by NPK fertilizer (23%), methanol (18%), and diesel oil (7%), while eutrophication and acidification indicated significant contributions from NPK fertilizer, methanol, diesel oil, and POME waste. These findings confirm the importance of utilizing POME waste as an optimal step to reduce CO_2 emissions with a potential reduction of up to 667.2 Kg CO_2 through a more sustainable biodiesel production life cycle concept. **Conclusion:** From this result, researchers recommend that palm oil companies start replacing chemical fertilizers with organic fertilizers to reduce environmental impacts, and encourage the utilization of POME waste at Palm Oil Mills as a source of biogas for renewable energy. At the biodiesel industry level, increasing the methanol recycling rate is proposed to improve efficiency and reduce emissions at the downstream stage of biodiesel production. **Novelty/Originality of this article:** This study identifies and evaluates alternatives for utilizing Palm Oil Mill Effluent (POME) waste with certain priority weights.

KEYWORDS: biodiesel; pome waste; palm oil; life cycle assessment.

1. Introduction

In September 2015, the concept of Sustainable Development was officially ratified, with 193 countries committing to achieve 169 targets in 17 Sustainable Development Goals (SDGs) by 2030. These goals include eradicating poverty and hunger, access to basic services, improving well-being, and protecting the environment (UN, 2015). The 2030 Agenda offers a framework for integrating social, economic and environmental aspects. Energy serves as one of the key factors in achieving the SDGs, and this has been recognized by various studies (McCollum et al., 2018; Nerini et al., 2018; Santika et al., 2019). Thus, energy is included in the seventh SDG (SDG7) that targets access to affordable, reliable,

Cite This Article:
Paminto, A. K. (2025). Utilization of POME waste as a renewable energy source in the life cycle concept of palm oil biodiesel. *Journal of Earth Kingdom, 2*(2), 96-112. https://doi.org/10.61511/jek.v2i2.2025.1276

sustainable and modern energy. SDG7 includes three main goals for 2030: universal energy access, increasing the proportion of renewable energy in global energy consumption, and improving energy efficiency.

In 2018, Indonesia produced 411.6 million tons of oil equivalent (Mtoe) from petroleum, natural gas, coal and renewables, with 64% or 261.4 Mtoe exported, dominated by coal and liquefied natural gas (LNG) (DEN, 2019a). More than 35% of energy demand in Southeast Asia is sourced from Indonesia (IEA, 2017b). However, Indonesia still imports energy, mainly crude oil and fuel products, around 43.2 Mtoe for the industrial sector. In 2018, national energy consumption (without traditional biomass) was 114 Mtoe, with the transportation, industrial, household, commercial, and other sectors consuming 40%, 36%, 16%, 6%, and 2%, respectively. Indonesia's oil production in the last 10 years declined from 949 thousand barrels per day (BOPD) in 2009 to 778 thousand BOPD in 2018, due to aging oil wells and limited new wells (DEN, 2019a; Haryanto, 2020; Nugroho, 2019).

Fossil fuels still play an important role as an energy source and raw material for downstream industries in Indonesia, but their use triggers global warming. Based on Government Regulation No. 79/2014 on the National Energy Policy, the renewable energy target is at least 23% by 2025 and 31% by 2050 (DEN, 2019b). The development of biodiesel as an alternative is expected to reduce dependence on petroleum imports, reduce greenhouse gas emissions, and support the economy through increased demand for plantation products (Pawar et al., 2018). The development of biodiesel continues in Indonesia.

At the global level, biofuel policies such as the Renewable Fuel Standard (RFS) in the United States, the Renewable Energy Directive in the European Union, and biofuel mandates in China and Brazil encourage the use of bio-based fuels. The shift to the bioeconomy is expected to improve sustainability (Rogers et al., 2016). Life Cycle Assessment (LCA) is a prevalent sustainability analysis method applied to biofuels, involving the systematic calculation of material and energy inputs and outputs at each stage of the life cycle, including energy and environmental impacts (Dunn, 2019). The focus of biofuel LCA is often on greenhouse gas emissions, although energy consumption, pollutant emissions and other factors must also be considered.

European and American countries state that biodiesel from palm oil still produces carbon in its production cycle (Siregar, 2014). Negative issues related to Indonesian palm oil have emerged such as a ban on biodiesel feedstock in the US starting in 2020 for not achieving the greenhouse gas emission reduction target of 20% of diesel oil emissions (4,224 Kg CO_2/ton), and a similar ban in the EU if it does not achieve a 35% reduction (Hasibuan et al., 2018). Meanwhile, research by Zutphen & Wijbrans (2011) put biodiesel emissions at 1,601 Kg CO_2/ton. If not managed properly, palm oil biodiesel production in Indonesia has the potential to negatively impact the environment (Wahyono et al., 2020). Therefore, LCA analysis of biodiesel production is needed to understand the emissions, environmental impacts, and opportunities for negative impact reduction, and to address biodiesel-related issues throughout the production chain.

2. Methods

This research was conducted using a quantitative approach. Based on the general objective, this research is categorized as developmental research, which develops an existing concept on biodiesel LCA. The proposed topic is the life cycle of palm oil biodiesel production with LCA. In addition to quantitative data in the preparation of the LCI, data or questionnaires from expert respondents to conceptualize the life cycle of palm oil biodiesel production. A full explanation of the data will be presented in the following sections. With an emphasis on quantitative approaches, the research objectives can be achieved in a measurable and more comprehensive manner.

Then, this research includes literature review, variable identification, field observation, LCI preparation, data analysis and interpretation. Data processing and interpretation used OpenLCA software. Observations and interviews were conducted on CPO production activities and biodiesel processes. These observations aimed to validate and complement the secondary data obtained. Observation and primary data collection activities were carried out at Cikasungka Plantation, Cikasungka Palm Oil Mill PTPN VIII and Lemigas KESDM. The research was conducted for 7 months starting from September to March 2022.

2.1 Research population and sample

Population is a set of data that has the same characteristics and is related to the life cycle of palm oil biodiesel production. The population in this research is the biodiesel production inventory data population and the respondent population. The inventory data population is all biodiesel production input and output data. Thus, this population reflects all data from the stages of oil palm plantation, CPO production, and biodiesel production. From this population, several criteria were determined for the sample.

The determination of this sample is done purposively with the criteria of functional unit of 1 ton of biodiesel, the reaction takes place by transesterification, the raw materials of CPO and production are located in Indonesia. In the biodiesel production stage, samples were taken from all material, energy and emission input and output data at the biodiesel plant of Lemigas KESDM. The population of expert respondents was all people directly and indirectly related to the biodiesel production system. From this population, a purposive sample was determined, namely experts who are directly related to biodiesel production and have at least 5 years of experience in the bioenergy sector. In this case, the sample of expert respondents came from several stakeholders, including the Ministry of Energy and Mineral Resources, PTPN VIII, academics and the National Research and Innovation Agency.

2.2 Research variables

Data collection related to the production and stages of the biodiesel process from palm oil was carried out through literature studies and visits to oil palm plantations, Cikasungka palm oil mill and biodiesel plants. Meanwhile, data for methanol and catalysts used literature studies and observations of biodiesel plants related to these production stages. Data related to Life Cycle Inventory was obtained from all processes of material input and output, energy and emissions during biodiesel production and entered into OpenLCA software. Meanwhile, data on the life cycle concept of biodiesel production was supported by expert respondents.

Data processing was carried out after the data was collected. The biodiesel production process data is processed based on the biodiesel life cycle. The results of data processing with OpenLCA software. Alternative hotspot points are processed from the questionnaire results using AHP. To aid analysis and interpretation, data needs to be presented appropriately. Data on the production stages are presented in the process flow, along with the results of the LCA or environmental impact calculations. The series of environmental impacts from the LCA results will be depicted in tables and diagrams. Finally, data interpretation is done with the output results of OpenLCA software. Comparison of the environmental impacts of each biodiesel production process and evaluation of the results of the OpenLCA software regarding these environmental impacts are carried out. Thus, hotspots or contributors to the greatest impact on the environment can be tracked.

Table 1. Research data matrix

No.	Data name	Source	Nature	How to collect or processing
1	Fresh Fruit Bunches (FFB)	Secondary	Quantitative	Observation and data
2	Fertilizer	Secondary	Quantitative	Observation and data
3	Water	Secondary	Quantitative	Observation and data
4	Herbicides	Secondary and Primary	Quantitative	Observation and data
5	Solar Oil	Secondary	Quantitative	Observation and data
6	CPO (*Crude Palm Oil*)	Secondary and	Quantitative	Observation and data

		Primary		
7	Electricity	Secondary	Quantitative	Observation and data
8	Water	Secondary	Quantitative	Observation and data
9	Solar Oil	Secondary	Quantitative	Observation and data
10	POME	Secondary and Primary	Quantitative	Observation and data
11	Biodiesel	Secondary and Primary	Quantitative	Observation and data
12	Methanol	Secondary and Primary	Quantitative	Observation and data
13	Sodium Hydroxide	Secondary and Primary	Quantitative	Observation and data
14	Electricity	Secondary	Quantitative	Observation and data
15	CO_2emission (eq)	Secondary and Primary	Quantitative	Open LCA software
16	*Acidification*	Secondary and Primary	Quantitative	Open LCA software
17	*Eutrophication*	Secondary and Primary	Quantitative	Open LCA software

2.3 Research analysis methods

2.3.1. Goal, scope, and inventory analysis

This step sets the context for the LCA study and is the basis for the definition of the objectives and scope. The functional unit defined is 1 ton of biodiesel. This unit will be the reference for all input data used. In addition to the functional unit, this step also defines the scope of the product system, determining which activities and processes are included in the biodiesel product life cycle (Hauschild, 2018). This step is the foundation for the inventory analysis step (Soukka et al., 2020).

Then, inventory analysis collects information about physical flows in relation to material inputs, energy and emission outputs. This step studies all processes identified as part of the product system, and is determined from functional units (Hauschild, 2018). These results are described in terms of numerical values and cover the entire life cycle (Klopffer & Grahl, 2014). The data can be obtained from several software such as OpenLCA, Simapro, GaBi, and others. The result of the inventory analysis is the life cycle inventory (LCI).

2.3.2 Impact assessment

In this process, inflows and outflows are linked to relevant impact categories, referred to as classification (Klopffer & Grahl, 2014). Impact assessment consists of several elements according to the ISO 14040 standard, namely selection of impact categories that represent the assessment parameters selected as part of the scope definition. For each impact category, indicators are selected along with an environmental model that can be used to measure the environmental impact; classification of basic flows from inventory data to impact categories according to the selected indicators; characterization using environmental models for the measured impact categories of the respective material, energy and emission flows.

The resulting impact characterization scores will be presented in an impact category matrix (Hauschild, 2018). The computational structure of LCA is modeled on matrix algebra, which is a mathematical calculation that formulates a collection of numbers arranged in a grid. rectangle systematically. For the computational calculation of LCA, it can be seen in Equation 1 (Maharjan et al., 2017).

$$As = f, Bs = g; g = BA\text{-}1f \qquad \text{(Eq. 1)}$$

A represents the technology flow matrix, B represents the environmental matrix, s is the scale vector for each process, f is the final demand of the product system, and g is the environmental impact under review. The inventory of A (i.e., quantity of input/output materials), while B (i.e., emission factors and energy consumption) is completed with a database in LCA software such as OpenLCA represents the technology flow matrix, B represents the environmental matrix, s is the scale vector for each process, f is the final demand of the product system, and g is the environmental impact under review. The inventory of A (i.e., quantity of input/output materials), while B (i.e., emission factors and energy consumption) is completed with a database in LCA software such as OpenLCA. In Equation 2 where 1 is for product f and 0 for all other products, a process- based model would be an analysis of the effects, impacts, or consequences caused by the consumption of 1 functional unit of product f in the modeled system (Yang, 2019).

$$f = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \tag{Eq. 2}$$

2.3.3 Acidification

Acidic gases such as sulfur dioxide (SO_2) react with water in the atmosphere to form "acid rain", a process known as acid deposition (Shammas et al., 2020). When this rain falls, often a considerable distance from the original source of the gas, it causes ecosystem damage in varying degrees, depending on the nature of the landscape ecosystem. Acidification of soil or aquatic ecosystems can be defined as an impact that leads to a decrease in acid-neutralizing capacity, i.e. a reduction in the amount of substances in the system that are able to neutralize hydrogen ions added to the system (Soudzilovskaia et al., 2010). According to Nilsson et al., 1982, stated that acid neutralizing capacity can be reduced by the addition of hydrogen ions, which replace other cations that can then be washed out of the system. And the absorption of cations in plants or other biomass that are collected and removed from the system.

Gases that cause acid deposition include ammonia (NH_3), nitrogen oxides (NO_x), and sulfur oxides (SO_x). Acidification potential is expressed using a reference unit, Kg SO_2 equivalent (Acero et al., 2016). The model does not account for regional differences in terms of which areas are more or less susceptible to acidification. It only accounts for acidification caused by SO_2 and NOx. This includes acidification due to the use of fertilizer, according to the method developed by the Intergovernmental Panel on Climate Change (IPCC).

2.3.4. Global warming potential, eutrophication, and interpretation

Climate change, defined as a change in global temperature resulting from the greenhouse effect due to human activities, poses significant environmental challenges. The scientific consensus highlights that increased emissions of greenhouse gases have a noticeable impact on the climate, making climate change one of the major environmental consequences of economic activity and one of the most complex issues to tackle due to its vast scale (Mikhaylov et al., 2020). The Environmental Profile characterization model, developed by the Intergovernmental Panel on Climate Change (IPCC), quantifies this impact using factors expressed as Global Warming Potential (GWP) over different timeframes, with 100 years (GWP100) being the most common reference, measured in Kg CO_2.

Eutrophication, the accumulation of chemical nutrients in ecosystems that leads to excessive productivity, significantly affects water quality and aquatic life (Weldeslassie et al., 2018). The excessive growth of plants, particularly algae in rivers, is driven by emissions of ammonia, nitrate, nitrogen oxides, and phosphorus into air or water, all of which contribute to this phenomenon (Liu, et al., 2020). Eutrophication is measured using the reference unit Kg PO_4^{3-} (eq), incorporating both direct and indirect impacts of fertilizers.

Additionally, the interpretation phase is the final step in Life Cycle Assessment (LCA), where conclusions are drawn from the calculations, and recommendations are developed in line with the study objectives. This phase considers the inventory analysis results and the characterization of impact assessment elements to address the defined objectives (Hauschild, 2018; Soukka et al., 2020).

3. Results and Discussion

The main focus of this study is one ton of biodiesel produced from palm oil, where the analysis includes all inputs and outputs within the boundary of the biodiesel production system. The location of the biodiesel plant of Lemigas KESDM from the Cikasungka palm oil mill is about 67.4 Km. In Table 2., the various inputs and outputs at each stage of biodiesel production are presented.

Tabel 2. Life cycle inventory produksi biodiesel (FU: 1 ton biodiesel)

Process Flow Unit Quantity	Flow	Unit	Quantity
Oil Palm Plantation	Dolomite	Kg	64.53
	Glyphosate	Kg	0.25
	Solar Oil	liter	0.41
	Plantation land	ha	0.46
	Pesticides	Kg	0.01
	NPK Fertilizer	Kg	141.11
	Truck Transpotation	t x Km	20
	Water	m^3	1570
	FFB	Ton	5.67
Palm Oil Mill	Electricity	kWh	16.31
	Solar Oil	liter	12.43
	PAC (Poly Aluminium Chloride)	Kg	0.28
	Shell	Kg	364.84
	Fiber	Kg	652.52
	Tankos	Kg	1267.58
	POME	m^3	3.47
	Water	m^3	5.20
	CPO	ton	1.17
Pilot Plant Biodiesel Lemigas-KESDM	Electricity	kWh	17.49
	Solar Oil	liter	15.64
	Metanol	t	0.41
	Sodium Hydroxide	t	0.01
	Transpotation	t x Km	67.40
	Water	Kg	3532.36
	Glycerol	Ton	0.09
	Biodiesel	Ton	1

In the production process, palm oil that has been processed through a transesterification reaction in a batch reactor is converted into biodiesel (Fig. 1). Transesterification is the most efficient method to convert CPO into biodiesel, with a conversion rate of 98%. To produce 1 ton of biodiesel, approximately 1.17 tons of CPO are required (Table 2.). The reaction produces two phases, a light-yellow top layer (FAME) and a dark brown bottom layer containing glycerol, which are then separated. The glycerol layer was separated, and the biodiesel obtained reached about 98% of the feedstock, although after several further processing steps, the final biodiesel yield reached 83%. In this reaction, 0.41 tons of methanol and 0.01 tons of sodium hydroxide catalyst were used to accelerate the transesterification process. The reactor temperature was maintained at 63°C for one hour with mixing and circulation to maintain solution homogeneity. The process consumes 17.49 kWh of electricity per ton of biodiesel at pilot plant scale.

Fig. 1. Biodiesel production transesterification reactor tank

After being separated from glycerol, the biodiesel then goes through a washing process (twice) with the same column for 30 minutes using hot water at 70°C to remove impurities. The biodiesel solution then undergoes a settling process before entering a vacuum dryer at 90°C and 70 cmHg pressure for 1-2 hours to reduce the water content before storage. A filtration process is also carried out to filter out any impurities that may remain in the biodiesel through a filter in the flow pipe.

The biodiesel produced has a final temperature of about 40-50°C and is piped to a storage tank. Glycerol as a by-product comes out from the bottom of the reactor. This by-product in the form of glycerol can be utilized in various industries (Ciriminna et al., 2014). Due to the impurity content of the Sodium Hydroxide catalyst, glycerol requires further processing in order to be used for the pharmaceutical, cosmetic, and tobacco industries. This is necessary because the high levels of free fatty acids and salts make crude glycerol unfit for use without further purification.

3.1 Analyze the environmental impacts of biodiesel production from cpo including CO_2 (eq) emissions, acidification and eutrophication.

3.1.1 Emisi CO_2 (eq) and eutrophication

Essentially, the temperature balance of the Earth's atmosphere is maintained through energy absorbed from solar radiation and energy reflected back into space, for example through reflection and infrared radiation. Of the sunlight that reaches the atmosphere, about 28% is reflected back by air molecules, clouds, and the Earth's surface, especially the ocean and ice regions such as in the Arctic and Antarctic, creating the albedo effect (Bais et al., 2015). The remaining radiation is absorbed by greenhouse gases (GHGs) in the atmosphere (21%) and the Earth's surface (50%) (Hauschild, 2018). This absorption heats the Earth's surface, which then releases energy in the form of infrared radiation with wavelengths longer than the incoming radiation. This infrared radiation is largely absorbed and stored by GHGs, increasing atmospheric temperature as GHG content increases. Compared to CO_2,

N_2O has a greater global warming potential, with a 298 times higher pollution effect (IPCC, 2013).

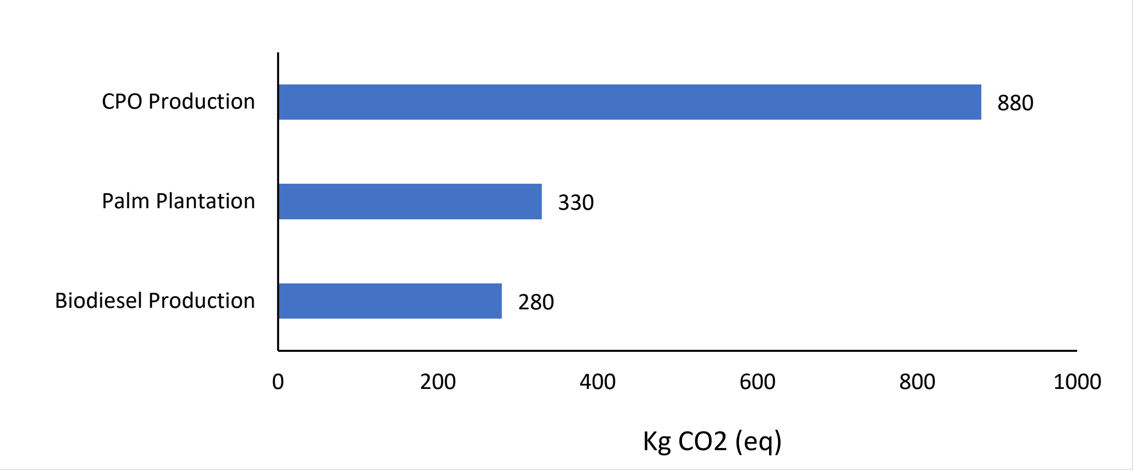

Fig. 2. CO_2 emission impact (eq) biodiesel production lifecycle

The potential CO_2 emissions from the entire biodiesel production life cycle are described in Fig 2., where 1 ton of biodiesel production generates 1489 Kg CO_2 (eq), with 26% contributed from the plantation phase, 53% from CPO production, and 21% from the biodiesel process. In the plantation phase, the use of NPK fertilizer contributes the largest emissions, at 22.7%, while transportation from the plantation to the palm oil mill contributes 2.8%. POME waste also contributed significantly to methane emissions at 768.6 Kg CO_2 (eq), and the biodiesel transesterification process accounted for 18.4% of emissions or 257 Kg CO_2 (eq) equivalent due to methanol use. Emissions from transportation and electricity use at the palm oil mill and biodiesel pilot plant contributed only a small amount, 1.04% and 0.02%, respectively.

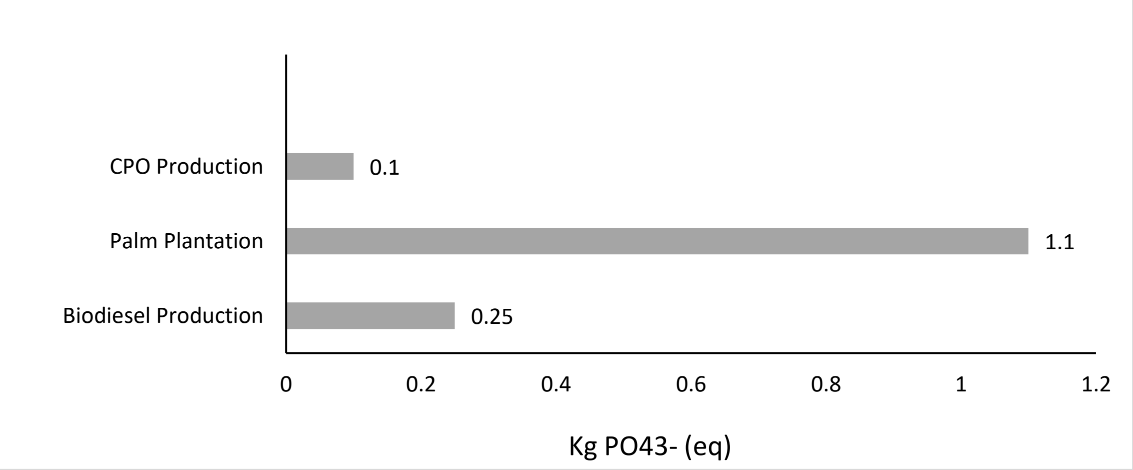

Fig. 3. Life cycle eutrophication impact of biodiesel production

In addition to CO_2 emission impacts, biodiesel production has the potential to cause eutrophication in water bodies such as lakes and rivers, which worsens water quality due to increased algae biomass that reduces oxygen levels and threatens biodiversity. The biodiesel plantation stage contributes the most to eutrophication, about 66% of the total impact of 1,115 Kg PO_4^{3-}(eq), followed by biodiesel production at 25%, and the CPO production stage at 9% (Fig. 3). The main cause is the use of NPK fertilizers, which contribute phosphorus and nitrogen emissions in the form of phosphate and nitrate, polluting water through runoff and increasing ammonia levels released into the air.

3.1.2 Acidification

Acidification occurs naturally, but is exacerbated by human activities such as agriculture and industry that increase hydrogen ions in the soil. The main source of acidification is the emission of gases that produce hydrogen when they decompose in the atmosphere or after falling onto soil, vegetation or water. Deposition through precipitation, or acid rain, can lower the pH of water to 3-4 under high air pollution conditions. According to the impact assessment of the CML (Institute of Environmental Sciences), the main acidifying compounds are Sulfur Oxides (SO_x) and Nitrogen Oxides (NO_x) that can turn acidic once oxidized in the troposphere (Guine´e et al., 2016).

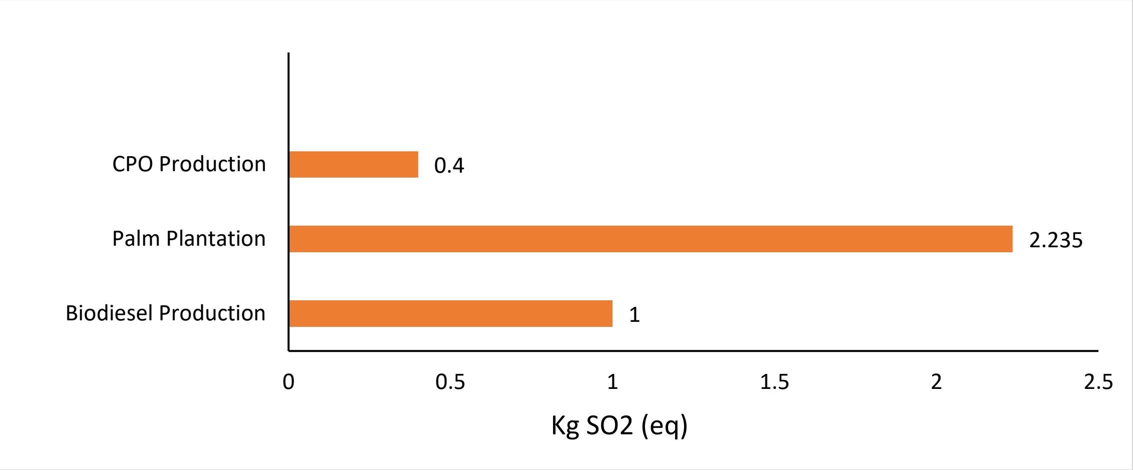

Fig. 4. Impact production biodiesel: acidification cycle life

The acidification potential of biodiesel production is 3,058 Kg SO_2 (eq), with the largest contribution from the plantation stage at 53%, followed by CPO production at 14%, and biodiesel production at 33%. The plantation stage contributes the largest impact due to the use of NPK fertilizers. Ammonia from fertilizers also increases acidification, which, when deposited on plants, can damage plant organs. When it reaches the soil, the pH of groundwater decreases, resulting in the release of metal ions that limit plant growth, and cause damage to roots and leaves.

3.2 Life cycle concept of palm oil biodiesel production

3.2.1 Biodiesel lifecycle hotspot analysis

The hotspot analysis helps to identify the source of the largest potential impact of CO_2 (eq) emissions, eutrophication, acidification in various phases of the biodiesel production life cycle. The largest contributor to CO_2 (eq) emissions is POME (Palm Oil Mill Effluent) at 768 Kg CO_2 (eq), followed by the use of NPK fertilizer (338 Kg CO_2 (eq)), methanol in the biodiesel plant (257 Kg CO_2 (eq)) and the use of diesel oil at 99 Kg CO_2 (eq). And the largest contributor to eutrophication emissions is the use of NPK fertilizer at 0.642 Kg PO_4^{3-} (eq), followed by the use of methanol (0.211 Kg PO_4^{3-} (eq)), the use of diesel oil at (0.127 Kg PO_4^{3-} (eq)), and POME waste at 0.084 Kg PO_4^{3-} (eq). Meanwhile, the largest contributor to acidification emissions is the use of NPK fertilizer at 1.361 Kg SO_2 (eq), followed by the use of methanol (0.795 Kg SO_2 (eq)), the use of diesel oil at 0.423 Kg SO_2 (eq), and POME waste at 0.385 Kg SO_2 (eq).

Burning fuels such as diesel oil emit various pollutants, such as CO_2, CO, NOx, etc., which contribute to the resulting emissions. However, this can be further reduced by improving the efficiency of diesel oil use. Such as the utilization of POME waste that produces biogas to be used as a cofiring substitute for diesel oil in the boiler, then the utilization of solid waste from CPO processing such as shells, fibers can be utilized in the boiler feed in producing diesel oil steam and electricity. Transportation including the use of diesel oil in trucks during operations at the plantation stage, transportation of FFB to the mill from the plantation site, delivery of CPO to the biodiesel plant to produce biodiesel contribute to CO_2 (eq) emissions. The development of an integrated biodiesel plant will be able to optimize the distribution of CPO thereby reducing transportation distances and thereby reducing GHG emissions.

The second contributor to CO_2 (eq) or GHG emissions comes from N_2O emissions in fertilization activities and NPK fertilizer production. During the plantation phase, the production of nitrogen fertilizer and its application to FFB production are the most polluting processes. The two types of emissions associated with agricultural production are direct and indirect emissions. Direct emissions result when N_2O is emitted directly into the atmosphere through planting and fertilizer application. Indirect emissions result from leaching and runoff. When large amounts of fertilizer N are lost from agricultural soils, they enter groundwater, riparian areas and wetlands, rivers and seas emitting ammonia or nitrogen oxides, causing N_2O production (Mosier, 1994). These values can be reduced to lower numbers by reducing the use of chemical fertilizers by applying more organic fertilizers and the use of empty fruit bunches to plantation land.

Fertilizers containing nitrogen, in the form of ammonium, can be converted to nitrate, which in turn lowers soil pH. Conversely, nitrification results in the formation of hydrogen ions (H^+) and has the potential to lower soil pH. Nitrate released into water can cause eutrophication, which is a direct result of algae growth (Huijbregts et al., 2017). According to Wantasen et al. (2012), the abiotic environment can be polluted by nitrogen transformations, including nitrate, nitrite, and ammonium. Nitrate is one of the nutrients that play a role in the growth of aquatic plants and algae, causing uncontrolled growth of aquatic flora, while killing other aquatic organisms. The methanol production process uses coal as fossil fuels that lead to the depletion of fossil fuels. SO_2 gas in the atmosphere can oxidize into the compound H_2SO_4, which in turn produces acid rain.

3.2.2. The best alternative for biodiesel production lifecycle optimization with method Analytical Hierarchy Process (AHP)

3.2.2.1. Prioritization of alternatives

The determination of alternatives is used to reduce the impact of emissions and make improvements in the biodiesel production process. The resulting alternative is not only one, but several alternatives are considered in decision making which will be determined by the Analytical Hierarchy Process (AHP) with the choice/justification of experts. Several alternatives were selected based on hotspots from the biodiesel production LCA model calculations that aim to reduce the impact of CO_2 (eq) emissions, eutrophication, and acidification in the biodiesel production life cycle.

Through the relationship between objectives, criteria, and alternatives, the selection of alternatives is selected based on complex problems in a hierarchy, and then the priority of these alternatives with other alternatives is evaluated numerically. From the selection of these priorities, an analysis is carried out to obtain alternatives that have the highest priority and have an impact on the results of the analysis. The stages of this analysis are as follows 1Identifying criteria in determining alternatives; 2) compiling a hierarchy of LCA impact category criteria; 3) determining priority weights by comparing between alternatives. Then 4) measuring the consistency value of the expert's choice in providing comparative values between alternatives. Then, from the results of the LCA hotspot points, it will produce an environmental impact comparison chart, and alternatives will be analyzed. There are three criteria used in this AHP analysis, namely the first criterion is CO_2 emissions (eq), the second criterion is eutrophication and the third criterion is acidification.

3.2.2.2. Hierarchical arrangement of alternatives

The problem to be solved is described in terms of separate elements. The focus of the problem is hierarchical, with the main problem being prioritized. How much influence do alternatives have on optimizing impact reduction in the biodiesel production life cycle. The problem to be solved in this study is to select the most optimal alternative that can be done in the biodiesel production life cycle.

The following is the hierarchical structure of the biodiesel production life cycle, shown in Fig. 5. The selection of alternatives in the biodiesel production process begins with a weighted comparison of each criterion. The selection process consists of 4 alternatives, namely (1) fertilizer (substitution of chemical fertilizer with organic fertilizer), (2) POME (utilization of Palm Oil Mill Effluent), (3) methanol (increasing the recycling rate of methanol in the biodiesel production process), and (4) biodiesel (efficient use of diesel oil). The four alternatives will be compared on each criterion with a priority assessment on one of the alternatives. One of the optimal alternatives will be obtained from the comparison results.

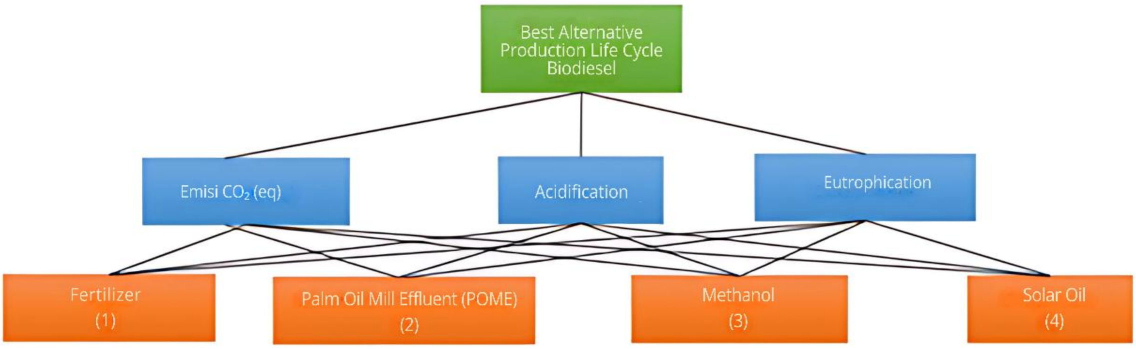

Fig. 5. Life cycle AHP structure of biodiesel production

3.2.2.3. *The best biodiesel lifecycle alternative*

The determination of the best alternative was based on the distribution of a questionnaire to resource persons who are experts and understand biodiesel production. From the questionnaire, possible alternatives were selected. The selection of resource persons was 15 (fifteen) people consisting of 2 experts from MEMR (Ministry of Energy and Mineral Resources), 4 experts from PTPN 8, 1 expert from the Professor of Defense University and 8 research experts from BRIN (Research and Innovation National Agency). Fifteen experts assessed the criteria and alternatives according to the questionnaire given. From the results of the questionnaire that has been filled in by expert respondents, the AHP matrix calculation is then carried out. Based on the results of the questionnaire, the weighting of criteria and alternatives is shown in Table 3. From the table, it is known that the weighting value of the fifteen experts for CO_2 (eq) emissions with acidification is 1.8645, CO_2 (eq) emissions with eutrophication is 2.1069, and acidification with eutrophication is 1.5349.

Table 3. Weighting of criteria

	CO_2 emission (eq)	Acidification	Eutrophication
CO_2 emission (eq)		1.86452	2.10698
Acidification			1.53492
Eutrophication			

The weighting value is based on the accumulation of selections that have been made by each expert. The following are the results of criteria assessment in Fig. 6 and alternative assessment in Fig. 7. In Fig. 6, it can be seen that the CO_2 emission criterion (eq) has a weight of 0.494, the acidification criterion (0.294), and the eutrophication criterion of 0.212. The total of the three criteria is 1.0, with the most significant weight being the CO_2 (eq) emission criteria.

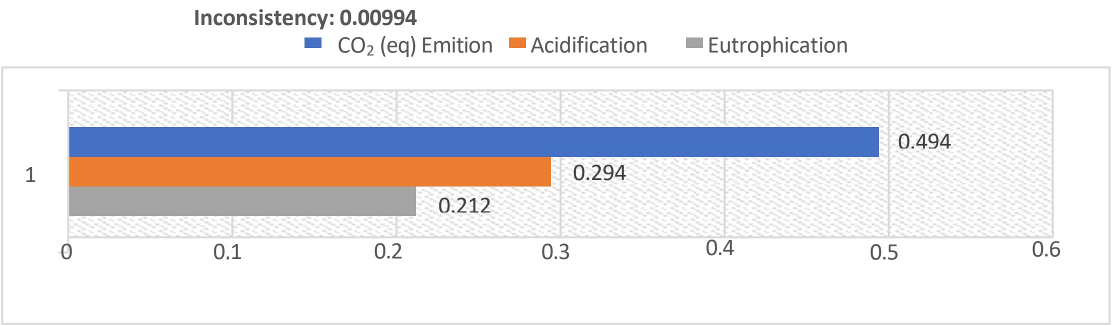

Fig. 6. Determination of AHP Criteria

From Fig. 7., the alternative of substituting chemical fertilizer to organic fertilizer has a weight of 0.335. The utilization of POME (Palm Oil Effluent Mill) is 0.357; increasing the recycling rate of methanol in the biodiesel plant is 0.135 and the efficiency of using diesel oil is 0.173. Of the three alternatives, the utilization of POME (Palm Oil Mill Effluent) is the best alternative in reducing environmental impact emissions from palm oil biodiesel production.

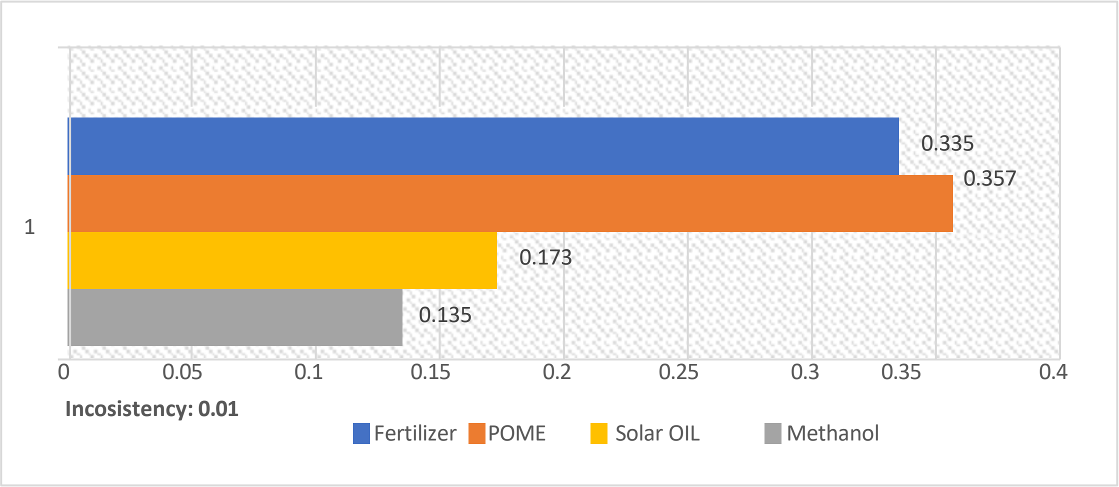

Fig. 7. Determination of multiple AHP alternatives

The utilization of POME with anaerobic wastewater treatment can reduce GHG emissions, because the methane content in POME is quite high. And the biogas potential from POME utilization is 22 m^3/ton POME (Castanheira & Freire, 2017), which can be utilized in generating electricity at the CPO Processing Plant. From the reference data in Table 4., the potential electricity generated by the Cikasungka CPO Plant is 90.68 kWh/ton of biodiesel, so it can be used to substitute electricity from PLN.

Table 4. POME utilization parameters

Parameters	Value	Unit	Reference
Volum of biogas	22	m^3/ton POME	Castanheira & Freire (2017)
Specific gravity of POME	0.876	tons/m^3	Ali & Tay (2013)
Methane (CH_4) content	60	%	Agrawal & Singh (2021)
Electricity from CH_4	2.04	kWh/m^3 CH_4	Dalpaz et al. (2020)

By optimizing the life cycle of biodiesel production by utilizing POME, the LCA model calculation obtained a decrease in emissions of 667.2 Kg CO_2 (eq), a decrease in eutrophication of 0.0074 Kg PO_4^{3-} (eq) and acidification of 0.335 Kg SO_2 (eq) (Fig.8.). Therefore, the total life cycle emission of biodiesel from palm oil by applying optimization is 823 Kg CO_2 (eq), eutrophication is 1,042 Kg PO_4^{3-} (eq) and acidification is 2.723 Kg SO_2 (eq). There is a life cycle optimization of biodiesel production with POME utilization.

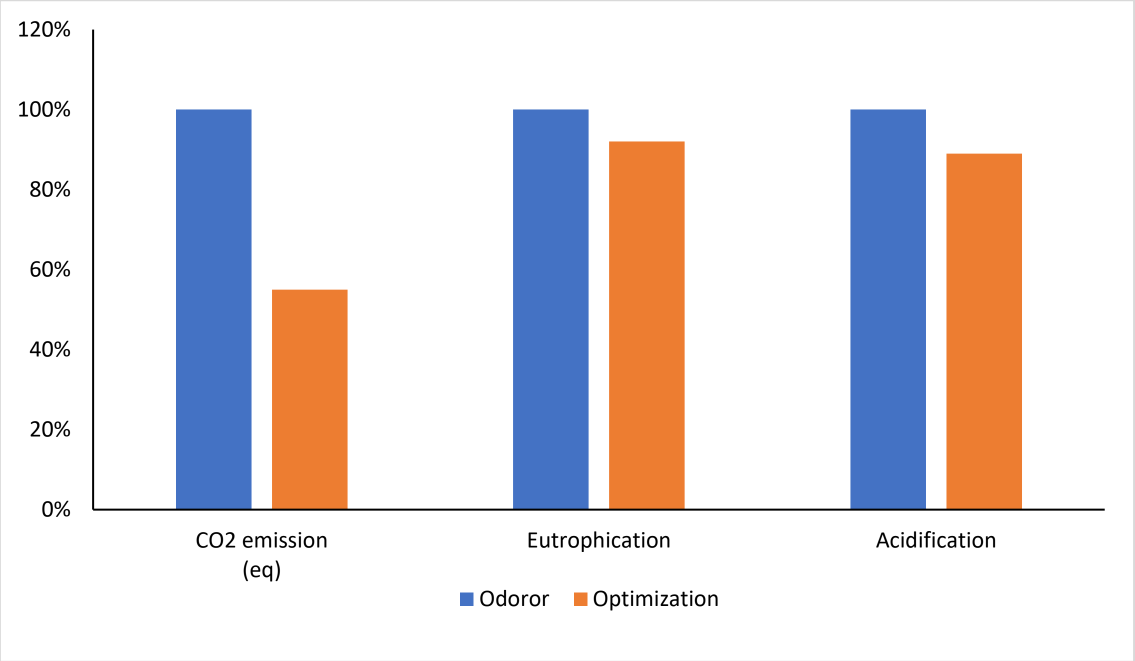

Fig. 8. Life cycle optimization of biodiesel production with POME utilization

This study shows that life cycle inventory (LCI) analysis is used to record the energy and material inputs and emission outputs at each stage of the life cycle of palm-based biodiesel production, from plantation, CPO production, to the biodiesel stage. In the production of 1 ton of biodiesel, the LCI data shows energy and material requirements such as NPK fertilizer (141.1 Kg), herbicide (0.25 Kg), water (1578 m^3), diesel oil (25 Kg), Fresh Fruit Bunches (FFB) (5.67 tons), electricity (33.8 kWh), and chemicals for the transesterification process: CPO (1.17 tons), methanol (0.41 tons), and Sodium Hydroxide (0.01 tons). In general, the use of fertilizers in this study is less than the research of Siregar et al. (2020) and Soraya et al. (2014), which reported using 1028 Kg, 463 Kg, and 199 Kg of fertilizer, respectively. This difference is due to the methods of each study; Siregar et al. (2020) included fertilizer use during the seedling process and TBM growth, while the organic fertilizer so that a larger amount was needed to meet nitrogen levels, and Soraya et al. (2014) reported a higher difference in tree density per hectare.

The study estimated total CO_2 (eq) emissions at 1489 Kg CO_2 (eq), eutrophication impacts at 1,115 Kg $PO4^3$- (eq), and acidification impacts at 3,058 Kg SO_2 (eq). These values are comparable to the findings of Yee et al. (2009) who recorded emissions of 1395 Kg CO_2 (eq), but in contrast to the reports of De Souza et al. (2010), and Siregar et al. (2014) which recorded emissions of 874 Kg, 2570 Kg, and 608.6 Kg CO_2 (eq), respectively. The difference is due to the utilization of POME and other solid waste calculated by De Souza et al. (2010), while the high GHG emissions in the study of Siregar et al. (2014) is due to the use of excess fertilizer in the early stages of oil palm growth, which increases N_2O emissions.

The results of this study also show that the largest impact on eutrophication and acidification comes from oil palm plantations, with a contribution of 66% and 53% respectively, which is in line with the findings of Phuang et al. (2021), where plantations made the dominant contribution to eutrophication and acidification at 67%. The difference in the Life Cycle Impact Assessment (LCIA) method with this study is an obstacle in comparing the absolute value of the impact.

The carbon footprint analysis shows that palm oil biodiesel production has several hotspots, including POME waste (53%), NPK fertilizer (23%), methanol (18%), and diesel oil (7%), a result in line with Zutphen & Wijbrans (2011) and Phuang et al. (2021) which recorded a contribution of POME of 60.18% to the total CO_2 (eq) emissions. Meanwhile, for eutrophication impacts, NPK fertilizer contributed 58%, followed by methanol (19%), diesel oil (11%), and POME (8%). In terms of acidification, the highest contribution also came from NPK fertilizer (45%), followed by methanol (26%), diesel oil (14%), and POME (13%). This finding is in line with the research of Siregar et al. (2020) and Soraya et al. (2014), although they did not detail the specific contribution of fertilizers to eutrophication and acidification. Significant differences were seen in the study of Yung et al. (2021) who used a narrower "gate to gate" scope at the biodiesel plant stage.

As a renewable energy source, sustainable biodiesel production can be achieved through optimal management at all stages of its life cycle. This study concludes that effective environmental impact reduction can be achieved by utilizing POME effluent generated from CPO processing plants. With an in-depth understanding of the impacts of CO_2 (eq), eutrophication, and acidification in the life cycle of palm biodiesel in Indonesia, the results of this study have the potential to make a significant contribution to government and company policy making, as well as a reference for further research in this area.

4. Conclusions

From the research results, some of the main conclusions can be explained as follows. First, the LCI (Life Cycle Inventory) shows that the production of 5.67 tonnes of Fresh Fruit Bunches requires 141.1 kg of NPK fertilizer, 0.25 kg of herbicide, 1570 m^3 of water, and 0.41 litres of diesel. For CPO production of 1.17 tons, 5.67 tons of Fresh Fruit Bunches, 16.31 kWh of electricity, 5.2 m^3 of water, 12.43 liters of diesel, and 3.47 m^3 of POME are required. Meanwhile, biodiesel production per ton requires 1.17 tons of CPO, 17.49 kWh of electricity, 15.64 liters of diesel, 0.41 tons of methanol, and 0.01 tons of sodium hydroxide. Second, total CO_2 (eq) emissions from biodiesel production reached 1489 kg CO_2 (eq), with the main contribution from CPO production, and the largest eutrophication and acidification in Fresh Fruit Bunch production. Third, the biodiesel life cycle concept can be optimized by utilizing POME waste to reduce emissions by 667.2 kg CO_2 (eq), with a priority weighting of 0.357 and a CO_2 (eq) emission criterion of 0.494.

Based on these findings, several suggestions are made. In terms of scientific development, the scope of the research can be extended to the application of biodiesel in vehicle engines for cradle to grave emissions evaluation. In terms of industry and government, it is proposed that oil palm plantations adopt organic fertilizers to reduce environmental impacts. Palm Oil Mills (PKS) can utilize POME waste as a source of electricity and boiler fuel. In addition, biodiesel plants need to increase methanol recycling for efficiency and emission reduction. The government is expected to incentivize research and development of environmentally friendly biomass energy.

Acknowledgement

The author would like to express their deepest gratitude to Dr. Mahawan Karuniasa and Dr. Evi Frimawaty for their invaluable guidance, helpful inputs, and unwavering support throughout this research. Their expertise and encouragement were crucial in the successful completion of this research.

Author Contribution

The author was solely responsible for the design and execution of the research, data analysis, interpretation of results, and manuscript preparation.

Funding

This research did not use external funding.

Ethical Review Board Statement

Not available.

Informed Consent Statement

Not available.

Data Availability Statement

Not available.

Conflicts of Interest

The author declare no conflict of interest.

Open Access

References

Acero, A. P., Rodriguez, C., & Ciroth, A. (2016). LCIA methods: Impact assessment methods in life cycle assessment and their impact categories. In *Green Delta*. https://www.openlca.org/wp-content/uploads/2015/11/LCIA- METHODS-v.1.5.4.pdf

Agrawal, R., & Singh, S. K. (2021). Modeling For The Energy Potential Of Biogas Power Plants In National Capital Territory. *Journal Of Critical Reviews, 8*(01), 631–658. https://jcreview.com/archives/volume-8/issue-1/6563

Ali, E. N., & Tay, C. I. (2013). Characterization of biodiesel produced from palm oil via base catalyzed transesterification. *Procedia Engineering, 53*, 7–12. https://doi.org/10.1016/j.proeng.2013.02.002

Bais, A. F., McKenzie, R. L., Bernhard, G., Aucamp, P. J., Ilyas, M., Madronich, S., & Tourpali, K. (2015). Ozone depletion and climate change: impacts on UV radiation. *Photochemical & Photobiological Sciences*, *14*(1), 19–52. https://doi.org/10.1039/C4PP90032D

Castanheira, É. G., & Freire, F. (2017). Environmental life cycle assessment of biodiesel produced with palm oil from Colombia. *International Journal of Life Cycle Assessment, 22*(4), 587–600. https://doi.org/10.1007/s11367-016-1097-6

Ciriminna, R., Pina, C. Della, Rossi, M., & Pagliaro, M. (2014). Understanding the glycerol market. *European Journal of Lipid Science and Technology, 116*(10), 1432–1439. https://doi.org/10.1002/ejlt.201400229

Dalpaz, R., Konrad, O., Cândido da Silva Cyrne, C., Panis Barzotto, H., Hasan, C., & Guerini Filho, M. (2020). Using biogas for energy cogeneration: An analysis of electric and thermal energy generation from agro-industrial waste. *Sustainable Energy Technologies and Assessments, 40*(67), 100774. https://doi.org/10.1016/j.seta.2020.100774

De Souza, S. P., Pacca, S., De Ávila, M. T., & Borges, J. L. B. (2010). Greenhouse gas emissions and energy balance of palm oil biofuel. *Renewable Energy, 35*(11), 2552–2561. https://doi.org/10.1016/j.renene.2010.03.028

DEN. (2019a). *Indonesia Energy Outlook*. National Energy Council.

DEN. (2019b). *Indonesia's Energy Security*. National Energy Council.

Dunn, J. B. (2019). Biofuel and bioproduct environmental sustainability analysis. *Current Opinion in Biotechnology, 57*, 88–93. https://doi.org/10.1016/j.copbio.2019.02.008

Guinée, J. B., Gorrée, M., Heijungs, R., Sleeswijk, A. W., Suh, S., Haes, H. A. U. de, Bruijn, H. de, Duin, R. van, & Huijbregts, M. A. J. (2016). *Handbook on Life Cycle Assessment Operational guide to the ISO standards*. Institute of Environmental Sciences-Leiden University (CML).

Haryanto, I. (2020). Regulation of Foreign Investments in The Development of New Renewable Energy (Ebt) in Indonesia. *Veteran Law Review, 3*(1), 12–21. https://doi.org/10.35586/velrev.v3i1.1458

Hauschild, M. Z. (2018). Life Cycle Assessment: Theory and Practice. Springer International. https://doi.org/10.1007/978-3-319-56475-3_6

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *International Journal of Life Cycle Assessment, 22*(2), 138–147. https://doi.org/10.1007/s11367-016-1246-y

IEA. (2017a). *Southeast Asia Energy Outlook 2017 - World Energy Outlook Special Report.* International Energy Agency.

IEA. (2017b). *World Energy Outlook*. iea.org

Klopffer, W., & Grahl, B. (2014). *Life Cycle Assessment (LCA)-A Guide to Best Practice*. Wiley-VCH.

Liu, X. J., Xu, W., Du, E. Z., Tang, A. H., Zhang, Y., Zhang, Y. Y., Wen, Z., Hao, T. X., Pan, Y. P., & Zhang, L. (2020). Environmental impacts of nitrogen emissions in China and the role of policies in emission reduction. *Philosophical Transactions of the Royal Society A, 378*(2183), 20190324. https://doi.org/10.1098/rsta.2019.0324

Maharjan, S., Wang, W. C., & Teah, H. Y. (2017). Life cycle assessment of palm- derived biodiesel in Taiwan. *Clean Technologies and Environmental Policy, 19*(4), 959–969. https://doi.org/10.1007/s10098-016-1290-0

McCollum, D. L., Echeverri, L. G., Busch, S., Pachauri, S., Parkinson, S., Rogelj, J., Krey, V., Minx, J. C., Nilsson, M., Stevance, A. S., & Riahi, K. (2018). Connecting the sustainable development goals by their energy inter-linkages. *Environmental Research Letters, 13*(3). https://doi.org/10.1088/1748- 9326/aaafe3

Mikhaylov, A., Moiseev, N., Aleshin, K., & Burkhardt, T. (2020). Global climate change and greenhouse effect. *Entrepreneurship and Sustainability Issues, 7*(4), 2897. https://doi.org/10.9770/jesi.2020.7.4(21)

Mosier, A. R. (1994). Nitrous oxide emissions from agricultural soils. *Fertilizer Research, 37*(3), 191–200. https://doi.org/10.1007/BF00748937

Nasreen, S., Nafees, M., Qureshi, L. A., Asad, M. S., Sadiq, A., & Ali, S. D. (2018). Review of catalytic transesterification methods for biodiesel production. *Biofuels: State of Development*, 93–119. https://doi.org/10.5772/intechopen.75534

Nilsson, S. I., Miller, H. G., & Miller, J. D. (1982). Forest growth as a possible cause of soil and water acidification: an examination of the concepts. *Oikos*, 40–49. https://doi.org/10.2307/3544529

Nugroho, H. (2019). Indonesia's Energy Development: Evaluation of the 2015- 2019 Medium Term Development Plan and Outlook for that of 2020-2024. *The Indonesian Journal of Development Planning, 3*(3), 266–272. https://doi.org/10.36574/jpp.v3i3.87

Pawar, R., Jagadale, K., Gujar, P., Barade, V., & Solankure, B. (2018). A comprehensive review on influence of biodiesel and additives on performance and emission of diesel engine. *Chemical Engineering Transactions, 65*, 451–456. https://doi.org/10.3303/CET1865076

Phuang, Z. X., Woon, K. S., Wong, K. J., Liew, P. Y., & Hanafiah, M. M. (2021). Unlocking the environmental hotspots of palm biodiesel upstream production in Malaysia via life cycle assessment. *Energy*, 232. https://doi.org/10.1016/j.energy.2021.121206

Rogers, J. N., Stokes, B., Dunn, J., Cai, H., Wu, M., Haq, Z., & Baumes, H. (2016). An assessment of the potential products and economic and environmental impacts resulting from a billion ton bioeconomy. *Biofuels, Bioproducts and Biorefining, 6*(3). https://doi.org/10.1002/bbb

Santika, T., Wilson, K. A., Meijaard, E., Budiharta, S., Law, E. E., Sabri, M., Struebig, M., Ancrenaz, M., & Poh, T. M. (2019). Changing landscapes, livelihoods and village welfare in the context of oil palm development. *Land Use Policy, 87*(June), 104073. https://doi.org/10.1016/j.landusepol.2019.104073

Shammas, N. K., Wang, L. K., & Wang, M.-H. S. (2020). Sources, chemistry and control of acid rain in the environment. In *Handbook of Environment and Waste Management: Acid Rain and Greenhouse Gas Pollution Control* (pp. 1–26). World Scientific.

Siregar, K., Ichwana, Nasution, I. S., Sholihati, Sofiah, I., & Miharza, T. (2020). Implementation of Life Cycle Assessment (LCA) for oil palm industry in Aceh Province, Indonesia. *IOP*

Conference Series: Earth and Environmental Science, 542(1). https://doi.org/10.1088/1755-1315/542/1/012046

Siregar, K., Sholiati, S., Sofiah, I., Miharza, T., Setyobudi, R. H., Anne, O., Wahyudi, A., Adinurani, P. G., & Mel, M. (2020). Review of Implementation Life Cycle Assessment for Biodiesel Production from Palm Oil (Elaeis guineensisJacq.) in Indonesia. In *E3S Web of Conferences* (Vol. 190, p. 21). EDP Sciences. https://doi.org/10.1051/e3sconf/202019000021

Soraya, D. F., Gheewala, S. H., Bonnet, S., & Tongurai, C. (2014). Life cycle assessment of biodiesel from palm oil in Indonesia. *Green Energy and Technology, 5*(9781447153634), 95–129. https://doi.org/10.1007/978-1- 4471-5364-1 5

Soudzilovskaia, N. A., Cornelissen, J. H. C., During, H. J., Van Logtestijn, R. S. P., Lang, S. I., & Aerts, R. (2010). Similar cation exchange capacities among bryophyte species refute a presumed mechanism of peatland acidification. *Ecology, 91*(9), 2716–2726. https://www.jstor.org/stable/27860848

Soukka, R., Väisänen, S., Grönman, K., Uusitalo, V., & Kasurinen, H. (2020). Life Cycle Assessment. *Sustainability Science*. https://doi.org/10.4324/9781315778730

UN. (2015). Transforming our world: The 2030 Agenda for Sustainable Development. 659 Resolution A/RES/70/1. https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A RES 7 0 1 E.pdf

Wahyono, Y., Hadiyanto, H., Budihardjo, M. A., & Adiansyah, J. S. (2020). Assessing the environmental performance of palm oil biodiesel production in indonesia: A life cycle assessment approach. *Energies, 13*(12). https://doi.org/10.3390/en13123248

Wantasen, S., Sudarmadji, Sugiharto, E., & Suprayogi, S. (2012). The Impact of Nitrogen Transformation on The Biotic Environment in The Lake Tondano North Sulawesi. *Manusia dan Lingkungan, 19*(2), 143–149. https://doi.org/10.22146/jml.18530

Yang, Y. (2019). A unified framework of life cycle assessment. *International Journal of Life Cycle Assessment*, 620–626. https://doi.org/10.1007/s11367-019-01595-w

Yee, K. F., Tan, K. T., Abdullah, A. Z., & Lee, K. T. (2009). Life cycle assessment of palm biodiesel: Revealing facts and benefits for sustainability. *Applied Energy, 86*(SUPPL.1), S189–S196. https://doi.org/10.1016/j.apenergy.2009.04.014

Yung, C. L., Subramaniam, V., & Yusoff, S. (2021). Life cycle assessment for the production of palm biodiesel. *Journal of Oil Palm Research, 33*(1), 140–150. https://doi.org/10.21894/jopr.2020.0080

Zutphen, J. M. Van, & Wijbrans, R. A. (2011). LCA GHG emissions in production and combustion of Malaysian palm oil biodiesel. *Jopeh: An official publication of the Malaysian Palm Oil Council (MPOC), 2,* 86–92. https://doi.org/10.5366/jope.2011.09

Biographies of Author

Ari Kabul Paminto, Environmental Science Study Program, School of Environmental Science, Universitas Indonesia, Depok, Jawa Barat, 16424; and 2 Badan Riset dan Inovasi Nasional (BRIN), Tangerang Selatan, 15314, Indonesia.

- Email: arik002@brin.go.id
- ORCID: 0000-0003-0081-7419
- Web of Science ResearcherID: N/A
- Scopus Author ID: 58638501100
- Homepage: https://scholar.google.co.uk/citations?user=YCCZPyAAAAAJ&hl=en&oi=ao