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MORALITY BEFORE KNOWLEDGE

Optimization of palm oil biodiesel production: Environmental impact analysis and POME waste utilization

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ABSTRACT
Background: Indonesia is still an energy importer, especially in the form of crude oil and fuel products to meet the needs of its industrial sector. The reduced production of fossil energy, especially oil, as well as the global commitment to reducing greenhouse gas emissions, has prompted the Indonesian government to continue to support the role of new and renewable energy. The production of palm oil-based biodiesel is faced with a number of environmental problems, which may occur from the release of emissions during the production of FFB (Fresh Fruit Bunches), CPO (Crude Palm Oil), and biodiesel. Therefore, the purpose of this research is to compile an LCI (Life Cycle Inventory) covering the production of FFB, CPO, and biodiesel; analyze the environmental impact of the CPO bodysel production process which includes CO_2 (eq) emissions, acidification and eutrophication; and develop a life cycle concept for biodiesel production from palm oil as a renewable energy. **Methods:** The method used in this study is a combination of quantitative LCA (Life Cycle Assessment) and AHP (Analytical Hierarchy Process) and qualitative. **Findings:** The results of this study are LCI in 1 ton of biodiesel consisting of NPK fertilizer of 141.1 Kg; herbicide (0.25 Kg); water (1578 m^3), diesel oil (25 Kg); fresh fruit bunches of 5.67 tons; electricity of 33.8 kWh, POME (Palm Oil Mill Effluent) (3,47 m^3), CPO needed for biodiesel conversion of 1.17 tons; methanol (0.41 tons), and 0.01 tons of Sodium Hydroxide. The total CO_2 emission (eq) of biodiesel production from palm oil is 1489 Kg CO_2 (eq), eutrophication is 1.12 Kg PO43- (eq) and acidification is 3.06 Kg SO_2 (eq). With the largest contribution of CO_2 (eq) emissions in CPO production and the contribution of eutrophication and acidification in oil palm plantations or FFB production (Fresh Fruit Bunches). Environmental hotspot of LCA, CO_2 (eq) emissions from palm oil biodiesel production show that 53% mainly comes from POME (Palm Oil Mill Effluent) waste, other contributors are NPK fertilizers (23%), methanol (18%), and diesel oil (7%). Hotspot eutrophication showed that 61% mainly came from NPK fertilizer, methanol (20%), diesel oil (11%), and POME waste (8%). Hotspot acidification showed that 48% mainly came from NPK fertilizers, methanol (28%), POME waste (13%), and diesel oil (11%). **Conclusion:** The concept of a biodiesel production life cycle can be applied with the best alternative utilization of POME waste with a priority weighting of 0.357 and a CO_2(eq) emission criterion of 0.494. From the optimization of the life cycle of biodiesel production with the use of POME, the potential for emission reduction is 667.2 Kg CO_2 (eq). **Novelty/Originality of this Study:** This study's novel application of LCA evaluates the environmental impacts of biodiesel production from palm oil in Indonesia, identifying critical hotspots in CO_2 emissions, eutrophication, and acidification. Additionally, it proposes an innovative optimization approach by utilizing POME to significantly reduce greenhouse gas emissions, highlighting a viable path for enhancing the sustainability of biodiesel production.

KEYWORDS: biodiesel; life cycle assessment; CO_2 (eq) emissions; acidification; eutrophication.

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1. Introduction

The integration of energy into the Sustainable Development Goals (SDGs), particularly through SDG7, emphasizes its crucial role in achieving sustainable development. SDG7 strives to guarantee access to affordable, reliable, sustainable, and modern energy for everyone, recognizing that energy is fundamental to numerous aspects of human development and well-being. Achieving these targets requires concerted efforts from governments, businesses, civil society, and international organizations. It involves implementing policies and regulations that promote sustainable energy access, fostering innovation and investments in renewable energy technologies, and scaling up energy efficiency initiatives. Furthermore, addressing barriers such as financing constraints, technological limitations, and institutional capacity gaps is crucial for accelerating progress towards SDG7 and advancing the broader agenda of sustainable development.

Indonesia's energy landscape in 2018 was dynamic, with notable production and consumption figures across various sectors. In 2018, Indonesia produced 411.6 million tons of oil equivalent (Mtoe) of primary energy. Of this total energy production, approximately 64% (261.4 Mtoe) was exported. Indonesia contributed over 35% of the total energy needs in Southeast Asian countries. Despite being a major energy producer, Indonesia still imported energy, specifically crude oil and fuel products, totaling 43.2 Mtoe to satisfy the demands of its industrial sector. In 2018, Indonesia's total energy consumption, excluding traditional biomass, was approximately 114 Mtoe. Overall, Indonesia's energy sector faces challenges in maintaining production levels, reducing import dependency, and meeting the diverse energy needs of its economy and population.

Currently, fossil fuels still play an important role not only as an energy source but also as raw materials for downstream industries in Indonesia. The current use of fossil fuels has had a global warming impact. The goals set by Government Regulation Number 79 of 2014 align with global efforts to transition towards sustainable energy systems. One alternative fuel policy is the development of biodiesel, so that it can reduce dependence on petroleum imports, reduce greenhouse gas emissions and revitalize the economy by increasing demand and prices for plantation products (Pawar et al., 2018). Biodiesel development in Indonesia is still ongoing today.

Policies promoting biofuels have indeed become prominent worldwide, with each region adopting its own strategies to enhance sustainability and reduce reliance on fossil fuels. The United States' Renewable Fuel Standard (RFS) mandates the blending of renewable fuels into transportation fuel. This policy aims to reduce greenhouse gas emissions and enhance energy security. In the same vein, the European Union's Renewable Energy Directive establishes targets for incorporating renewable energy sources, including biofuels, to combat climate change and encourage sustainable development. In China and Brazil, mandatory biofuel blending programs have been implemented to address environmental concerns and reduce dependence on imported oil.

European and American countries claim that biodiesel produced from palm oil will continue to emit carbon into the atmosphere throughout its production cycle (Siregar, 2014). Some of the negative issues used to curb the dominance of Indonesian palm oil are that it is not allowed Indonesian palm oil as raw material for the biodiesel industry in the United States starting in 2020, because it does not achieve a reduction in greenhouse gas emissions (the default value of GHG emission savings) of 20% from diesel oil emissions (4224 Kg CO_2/ton of diesel oil), and the EU through RED (Renewable Energy Directive) assesses that Indonesian biodiesel does not reach GHG emissions (the default value for emission savings) of 35% as a requirement for an environmentally friendly product (Hasibuan et al., 2018). Meanwhile, from research by Zutphen & Wijbrans (2011), biodiesel emissions were 1601 Kg CO_2/ton. Palm oil biodiesel production in Indonesia, while offering potential benefits in terms of renewable energy and economic development, also presents significant environmental challenges if not managed sustainably (Wahyono et al., 2020). Therefore, LCA (Life Cycle Assessment) analysis is needed in biodiesel production so that we know the impacts of emissions, the environment and the potential to reduce these impacts. And in the future we will be able to overcome negative issues related to the biodiesel industry both in the upstream and downstream sectors.

2. Methods

2.1 Time, place, and research approach

This research was conducted using a quantitative approach, focusing on the life cycle assessment (LCA) of biodiesel production from palm oil. Based on its general objectives, it falls under the category of developmental research, aimed at further developing existing concepts related to biodiesel LCA. The primary topic addresses the entire life cycle of biodiesel production from palm oil. To support this, quantitative data for the life cycle inventory (LCI) is crucial, but input from expert respondents or specialists is also necessary. This input, gathered through data collection or questionnaires, helps formulate a comprehensive understanding of the production cycle. A detailed explanation of this data will be presented in subsequent sections. With the emphasis on a quantitative approach, the research objectives are expected to be achieved in a measurable and thorough manner, ensuring a robust analysis. The research involved several activities, including literature reviews, variable identification, field observations, compiling the LCI, and subsequent data analysis and interpretation. The processing and interpretation of data were conducted using OpenLCA software, which is designed for LCA studies.

Observations and interviews were also carried out, specifically focused on crude palm oil (CPO) production and the biodiesel process. The aim of these observation activities was to validate and supplement secondary data obtained from previous research. These activities, along with the primary data collection, took place at Cikasungka Plantation, Cikasungka Palm Oil Factory (PTPN VIII), and Lemigas KESDM.

2.2 Research population, sample, and variabels

Population refers to a set of data that shares similar characteristics and pertains to the life cycle of palm oil biodiesel production. In this context, "population" includes both the inventory data population, which comprises all input and output data related to biodiesel production, and the population of respondents, referring to individuals providing data or insights relevant to the study. Thus, this population encompasses all data pertaining to the stages of oil palm plantations, crude palm oil (CPO) production, and biodiesel production.

From this population, several criteria are established to select the sample. The sample selection is purposive and based on functional criteria, specifically involving a 1-ton biodiesel unit, the use of transesterification in the reaction process, and the sourcing of CPO raw material and production in Indonesia. In the biodiesel production stage, samples are taken from all material, energy and emission input output data at the KESDM Lemigas biodiesel plant. The population of expert respondents is all people who are directly and indirectly related to the biodiesel production system.

From this population, a sample was determined purposively, namely experts who were directly related to biodiesel production and had 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. Furthemore, the main variables used in this research are given operational boundaries or definitions to facilitate analysis. Operational definitions of all the main variables used in this study are presented.

2.3 Research data

Research data is a form of measurement of the research variables described previously. This data undergoes several processes, such as collection, processing, presentation, analysis and interpretation. Data collection concerning the production and process stages of biodiesel from palm oil involved literature reviews and visits to palm oil plantations, the Cikasungka palm oil mill, and the biodiesel plant. Information on methanol and catalyst usage was obtained through literature reviews and observations at biodiesel plants during the production stages. Life Cycle Inventory (LCI) data encompassed all material inputs and outputs, energy consumption, and emissions during biodiesel production, which were input into OpenLCA software. Expert respondents provided data and insights supporting the life cycle concept of biodiesel production.

Data processing is carried out after the data is collected. Biodiesel production process data is processed based on the biodiesel life cycle. 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 production stages is presented in the process flow, together with the results of LCA or environmental impact calculations. Data interpretation is carried out using the output of the OpenLCA software. Comparison of the environmental impact of each biodiesel production process and evaluation of the OpenLCA software results regarding the environmental impact. So, hotspot points or contributors to the biggest impact on the environment can be tracked.

2.4 Research analysis methods

The data analysis for this research primarily uses the Life Cycle Assessment (LCA) method, which is divided into four key phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. Each phase plays a critical role in understanding and evaluating the environmental impacts of biodiesel production. The first phase, goal and scope definition, sets the foundation of the LCA study. It establishes the context by defining the objectives and scope of the assessment. For this research, the functional unit is set as 1 ton of biodiesel, which serves as the reference point for all input data used throughout the study. Along with defining the functional unit, this phase also determines the boundaries of the product system, outlining which activities and processes are included in the biodiesel life cycle. This step is essential for setting the groundwork for the subsequent inventory analysis (Hauschild, 2018).

The second phase, inventory analysis, involves collecting and quantifying data related to the physical flows of material inputs, energy use, and emission outputs. This stage covers all processes identified as part of the product system, starting from the functional unit. The results, presented as numerical values, represent the entire life cycle of biodiesel production (Klopffer & Grahl, 2014). Data for this analysis can be gathered from software tools like OpenLCA, Simapro, or GaBi. The outcome of this step is the life cycle inventory (LCI), which serves as the input for the next phase of impact assessment.

In the third phase, impact assessment, the inputs and outputs from the inventory are classified into relevant environmental impact categories. According to the ISO 14040 standard, this phase involves selecting impact categories, classifying inventory data into these categories based on predefined indicators, and characterizing the environmental impacts using models that measure the effect of material, energy, and emission flows. The result of this process is presented in an impact category matrix, showing the environmental impact scores for each category (Hauschild, 2018; Klopffer & Grahl, 2014).

2.4.1 Acidification

Acid gases like 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 acidic precipitation falls, often far from its original emission source, it can cause varying degrees of damage to ecosystems, depending on their landscape and characteristics. Acidification of soil or water ecosystems results in a decrease in their acid neutralizing capacity, meaning there are fewer substances available within the system to neutralize added hydrogen ions (Soudzilovskaia et al., 2010). Nilsson et al. (1982) explain that the acid neutralizing capacity can be reduced by the influx of hydrogen ions, which displace other cations that are subsequently leached out of the system. Moreover, the uptake of cations by plants or other biomass, which are later harvested and removed from the system, also contributes to lowering the acid neutralizing capacity.

Gases contributing to acid deposition include ammonia (NH3), nitrogen oxides (NOx), and sulfur oxides (SOx). Acidification potential is quantified using reference units, typically expressed as Kg SO_2 equivalents (Acero et al., 2016). The model used does not consider regional variations in vulnerability to acidification, focusing solely on the impacts of SO_2 and NOx. This assessment encompasses acidification resulting from fertilizer use, based on methodologies developed by the Intergovernmental Panel on Climate Change (IPCC).

2.4.2 Global warming potential and eutrophication

Climate change, a major environmental issue, is driven by the increase in global temperatures due to the greenhouse effect, which stems from the release of greenhouse gases through human activities. The scientific community widely agrees that these heightened emissions are having a substantial impact on the climate, with climate change being a significant environmental consequence of various economic activities. Mitigating climate change is particularly challenging due to its global scale and the complexities involved in addressing the many contributing factors (Mikhaylov et al., 2020). To measure and evaluate these effects, the Environmental Profile characterization model uses factors developed by the Intergovernmental Panel on Climate Change (IPCC). These factors are typically expressed as Global Warming Potential (GWP) over different time periods, most commonly the 100-year time frame (GWP100), with results measured in kilograms of CO_2 equivalents (eq).

Another critical environmental issue, eutrophication, refers to the excessive build-up of chemical nutrients within an ecosystem, which leads to abnormal levels of productivity (Weldeslassie et al., 2018). This phenomenon causes accelerated plant growth, particularly of algae in aquatic systems, which severely deteriorates water quality and impacts animal populations. Eutrophication is driven by the release of substances like ammonia, nitrate, nitrogen oxides, and phosphorus into both air and water systems (Liu et al., 2020). The environmental impacts of eutrophication are quantified using the reference unit Kg PO43- (eq), which captures the direct and indirect effects of fertilizers and other contributors in this process.

2.4.3 Interpretation

The fourth and final step in LCA is interpretation. In this phase, conclusions are drawn from the results of LCA calculations, and recommendations are formulated in accordance with the study objectives. Research findings are analyzed to address the questions posed in the objectives, considering data from inventory analysis and the characterization of impact assessment elements (Hauschild, 2018; Soukka et al., 2020).

The Analytic Hierarchy Process (AHP) is used to gauge the judgments of experts or decision-makers by conducting pairwise comparisons of elements. A sub-problem hierarchy is constructed in AHP, outlining a decision problem that can be evaluated subjectively. After converting these subjective evaluations into numerical values, each alternative is numerically ranked. The AHP method consists primarily of four steps: (a) developing a hierarchical structure, (b) conducting pairwise comparisons between criteria and alternatives, (c) synthesizing priorities, and (d) checking for consistency (Ilham & Nimme, 2019; Saaty, 2008). Questionnaires were distributed to respondents, including experts from academia, government, and biodiesel environmental experts in Indonesia, to determine the weighting of each environmental category. Individual assessments were gathered by eliciting relative pairwise comparisons between environmental impact categories such as Global Warming Potential (GWP), Acidification, and Eutrophication.

These assessments provided an alternative to pinpoint hotspot areas in the LCA model output.

The weighting intensity in the Analytic Hierarchy Process (AHP) ranges from 1 to 9, where 1 signifies equal importance, 3 indicates slight preference over other elements, 5 denotes moderate importance, 7 signifies strong importance, and 9 represents absolute importance. The values 2, 4, 6, and 8 are intermediate values between these assessments, reflecting varying degrees of importance relative to each other. This scale allows for the relative measurement of intangible qualities. In AHP, pairwise comparisons are made using an absolute rating scale to determine how much one element dominates another in terms of a given attribute (Saaty, 2008). The pairwise comparison matrix, A1, is an (n x n) matrix where n is the number of criteria. The priority vector, A2, is then derived to calculate the average weight matrix. The priority vector A2, which indicates the relative importance of each criterion compared to others, is obtained by computing the geometric mean of each row of matrix A1 (Saaty, 1990).

3. Result and Discussion

3.1 Description of research area

3.1.1 PT Perkebunan Nusantara VIII

PT Perkebunan Nusantara VIII, a State-Owned Enterprise, engages in the management, processing, and marketing of various plant products. These commodities include palm oil, rubber, tea, coffee, cocoa, and fruit. In an effort to bolster the role of State-Owned Enterprises (BUMN) in the plantation sector within the framework of national development and economic advancement, as well as to prepare for global economic shifts, the government, in collaboration with the Ministry of Agriculture, has initiated a program to consolidate all national plantations. The aim and objective of establishing PTPN VIII are to operate in the agro-industry sector and optimize the utilization of PTPN resources to produce high-quality and competitive goods and/or services. The business activities are centered at the Directors' Office located at Jl. Sindangsirna No. 4, Bandung, West Java, spanning across 11 regencies/cities in West Java (Bogor, Sukabumi, Cianjur, West Bandung Regency, Bandung City, Subang, Purwakarta, Garut, Tasikmalaya, and Ciamis) and 2 regencies in Banten Province (Lebak and Pandeglang).

Fig. 1. PTPN VIII palm oil plantation
(PTPN VIII, 2022)

PT Perkebunan Nusantara VIII (PTPN VIII) operates oil palm plantations in two regions: West Java and Banten. PTPN VIII manages a total of 10 plantation units for developing oil palm plantations, including Kertajaya, Bojong, Cibungur Datar, Cikasungka, Cisalak Baru, Sukamaju, Gedeh, and Tambaksari, covering approximately 20,154 hectares, which constitutes 18% of its total agricultural area (PTPN VIII, 2022a). The palm oil produced is marketed domestically as Crude Palm Oil (CPO) and Kernel. Additionally, PTPN VIII operates two palm oil processing factories: the Kertajaya factory and the Cikasungka factory. One of the research locations is situated at the Cikasungka Plantation and Cikasungka CPO Processing Factory in Cigudeg sub-district, Bogor Regency (Fig. 1.). The Cikasungka plantation employs 359 individuals, with 45 staff members in the plantation office and 6 retired employees.

3.1.2 LEMIGAS–KESDM (ministry of energy and mineral resources)

The Oil and Gas Technology Research and Development Center (LEMIGAS) is a government research institution specializing in the upstream and downstream sectors of the oil and gas industry. Established on June 11, 1965, LEMIGAS functions as a center for collecting and advancing technical knowledge within the oil and gas sector, providing essential data and information required by decision-makers (KESDM, 2020). LEMIGAS operates under the Energy and Mineral Resources Research and Development Agency and is classified as a second-level government technology implementation unit within the Ministry of Energy and Mineral Resources.

The position of LEMIGAS within the organizational structure of the Ministry of Energy and Mineral Resources is defined by Minister of Energy and Mineral Resources Regulation Number 13 of 2016, which outlines the organization and operational procedures of the ministry (Fig. 2.). LEMIGAS operates under the Public Service Agency Financial Management Model (PPK BLU), as governed by Minister of Energy and Mineral Resources Regulation Number 24 of 2014 (KESDM, 2020). This implementation of BLU PPK is part of LEMIGAS' commitment to enhancing governance and aligns with the Ministry of Energy and Mineral Resources' objective of improving government services to the national oil and gas industry.

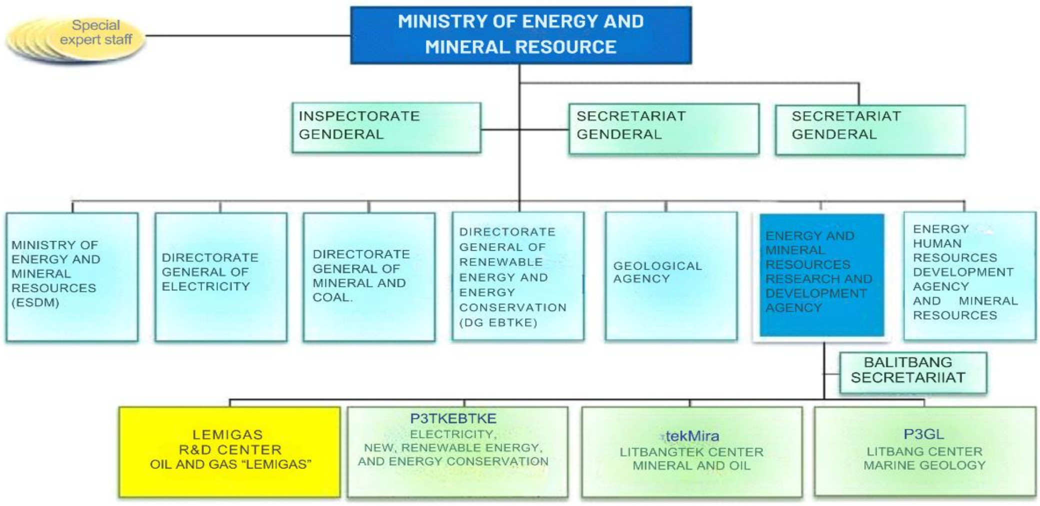

Fig. 2. LEMIGAS's position in the organizational structure of the Ministry of Energy and Mineral Resources
(KESDM, 2020)

LEMIGAS carries out research, development, engineering, studies and services in the oil and gas sector. In carrying out this task, LEMIGAS carries out the following functions (KESDM, 2022): 1) formulating technical policies, plans and research programs; 2) carrying out research, development, technological engineering, survey research and services, knowledge management and innovation; 3) monitoring, evaluating and reporting on research, development and technological engineering as well as implementation of research in the oil and gas sector; 4) development of quality policies and work procedures; 5) management of the oil and gas industry research environment, occupational safety and health in technology development services. The construction of a biodiesel pilot plant at the Lemigas office, Cipulir, South Jakarta began in 2000 with the completion and operation of a biodiesel pilot plant with a capacity of 100 liters/batch, and continued in 2006 with the restoration of the pilot plant to 150 liters/batch and a biodiesel pilot plant with a capacity of 8 to 10 tons/day and a 30 ton/day biodiesel plant in Rokan Hulu Riau in 2007.

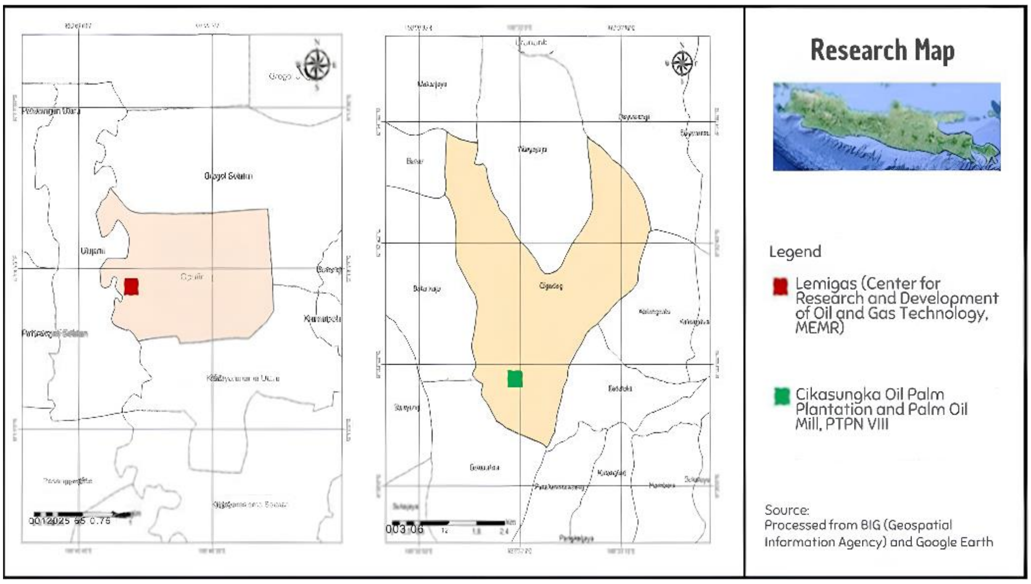

Fig. 3. Map of research locations for Cikasungka plantation, Cikasungka palm oil factory PTPN VIII and Lemigas-KESDM

3.2 Compiling the LCI includes FFB, CPO and biodiesel production

Data on the production process of palm oil mills were gathered from mills situated in Bogor Regency, West Java Province, Indonesia, near the Cikasungka oil palm plantation. Concurrently, data concerning the biodiesel production process were collected from the biodiesel pilot plant at LEMIGAS (Center for Research and Development of Oil and Gas Technology) in Indonesia. The functional unit utilized for this research is 1 ton of biodiesel.

The limitation of this research lies in its cradle-to-gate system. Begins the assessment from the production of raw materials (fresh fruit bunches) through to the production of biodiesel products. The cradle-to-gate life cycle of biodiesel production from palm oil comprises three main processing units: palm plantations for producing Fresh Fruit Bunches (FFB), the production of Crude Palm Oil (CPO), and the biodiesel production process itself to manufacture biodiesel.

3.2.1 TBS production inventory life cycle

The oil palm cultivation stage was inventoried for the PTPN 8 oil palm plantation in Cikasungka which consists of 6 afdelings. Data for activities outside the Cikasungka Palm Oil Plantation and Factory, such as fertilizer, fuel and machinery production, were obtained from the LCA database. The process of oil palm plantation involves cultivation, maintenance, and harvesting. The entire plantation cycle spans 25 years, comprising a 3-year period for the young oil palm nursery phase and approximately 22 years dedicated to oil palm cultivation. The inventory data for oil palm plantations in 2020 from the Cikasungka plantations are detailed in Table 1. The total plantation area across six sections of Cikasungka amounts to 3,500 hectares.

Oil palm seedlings undergo cultivation for 12-13 months before being transferred to the plantation site. Prior to relocation, a survey is conducted, involving the removal of existing vegetation. Infrastructure such as roads and field drainage systems are constructed, and various soil conservation measures like terraces, embankments, and mud pits are implemented to prepare the plantation area. The planting phase is on the Cikasungka plantation which has high rainfall on average of 2628 mm per year with a plantation location of 100 meters above sea level. The density of oil palm trees planted in the Cikasungka plantation area is around 121 trees/ha, with a tree to tree distance of 9 meters.

Due to limited data available, and the research location, in this case the Cikasungka plantation, does not carry out nurseries, the nursery stage is not included in the LCA boundary of this study. Plant maintenance is divided into two periods, namely when the plants are not yet mature (TBM) and when the plants are mature (TM). Intensive maintenance is needed for optimal growth so as to produce good products. Immature Plants (TBM) occur at the age of 3 years and under and Mature Plants (TM) are further maintenance activities that occur at the age of 3-25 years. After 25 years, re-planting is usually carried out. During maintenance activities, fertilization, leaf pruning and pest control are carried out. Oil palm nutrient needs are met by applying fertilizer and residue from palm oil mills (empty fruit bunches) which are applied to Cikasungka plantations to obtain optimal production. The application of fertilizers in plantations, along with the average annual nutrient use of NPK inorganic fertilizers, as well as the use of herbicides and pesticides, are detailed in Table 1. Throughout the oil palm growth cycle, integrated pest management practices are employed to effectively control and minimize crop losses caused by pests. In the Cikasungka garden, natural insecticides are also applied using owls. This has been implemented in 4 afdelings, where each afdeling has 6 owls.

Table 1. Life cycle inventory (LCI) for palm oil plantations in 2020

Flow	Units	Amount
Dolomite	Kg	11.37
Glyphosate	Kg	0.04
Diesel Oil	litre	0.07
Land	ha	0,08
Pesticide	Kg	0.001
NPK Fertilizer	Kg	24.87
Transportation	t×km	20
Water	m^3	277
TBS	tons	1

The harvest from oil palm plants is fresh fruit bunches, so harvesting is the final activity in the oil palm cultivation process. When cutting FFB, you must pay attention to the maturity level of the fruit because it affects the quality of the palm oil that will be produced. The harvest of fresh fruit bunches typically begins between 2.5 to 3 years after planting in the field, varying depending on soil type and the management practices implemented for the plants. Harvested fresh fruit bunches must be immediately transported to the factory for further processing. If FFB is not processed immediately, the FFA content will increase. To avoid this, FFB must be processed immediately within a maximum of 8 hours after harvest. Palm oil plantations require various material and fuel inputs, which include NPK fertilizer, dolomite, herbicide (glyphosate), water for irrigation, land for cultivation, and diesel oil for truck transportation. And the product produced by oil palm plantations is FFB. Palm oil plantations also have emissions output, including air emissions, such as CO_2 and N_2O.

3.2.2 CPO production inventory life cycle

Life Cycle Inventory CPO Production involves the CPO production process at the Cikasungka PKS (Palm Palm Factory). The palm oil factory is close to an oil palm plantation and it is estimated that the distance to the palm oil processing process is 20 km. The harvested FFB is then sent to the factory to carry out further processing and produce CPO. Products from PTPN 8 are for domestic consumption and not yet exported. During the harvest period, crude palm oil (CPO) typically contains 0.5% free fatty acids (FFA). To prevent a quick rise in FFA levels caused by enzymatic processes (which can occur if fresh fruit bunches are bruised or damaged), the fresh fruit bunches (FFB) are promptly processed to produce high-quality CPO. The extraction of CPO from FFB at PTPN 8 involves multiple stages, with detailed sub-processes depicted in Fig. 4. of the palm oil life cycle inventory (LCI).

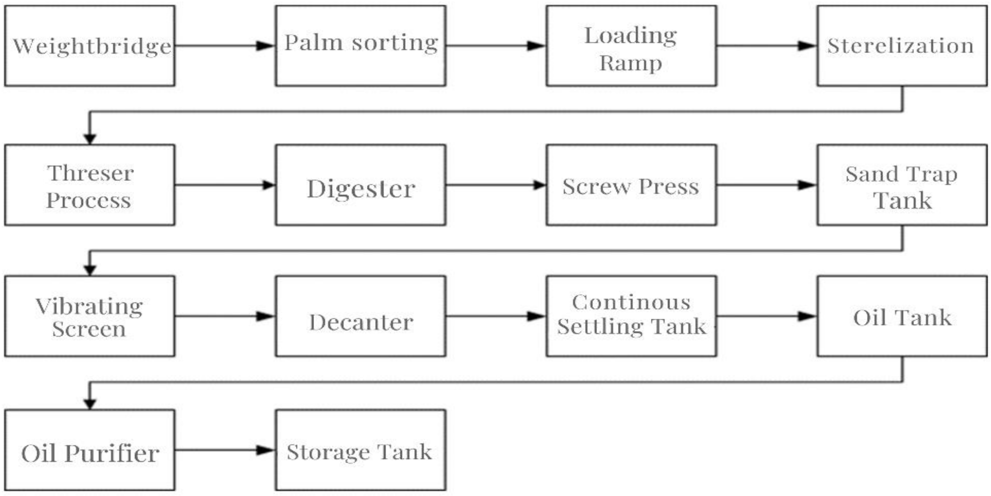

Fig. 4. CPO production process at the Cikasungka factory PTPN VIII

3.2.3 Life cycle inventory biodiesel

The research utilizes a functional unit of 1 ton of biodiesel derived from palm oil. This inventory consists of all inputs and outputs from the biodiesel production system boundary. The distance between the Lemigas (Research and Development Agency) KESDM biodiesel plant and the Cikasungka palm oil mill is estimated to be 67.4 km. To date, the transesterification process is the most optimal process for converting CPO into biodiesel, the conversion of CPO into biodiesel has a conversion rate of 98%, the CPO raw material used for biodiesel production is 1.17 tonnes of biodiesel.

From the reaction, two phases are produced. Subsequently, settling is conducted, resulting in a light yellow liquid (FAME) forming the top layer, while glycerol forms the bottom layer as a dark brown liquid. After that the bottom layer is removed (Glycerol), and the top phase (Biodiesel) is obtained approximately 98% from the raw material feed, but with several subsequent processes the weight of the biodiesel will be reduced, with a yield of 83%. The methanol used was 0.41 tons and the Sodium Hydroxide catalyst was 0.01 tons. This catalyst functions to speed up the transesterification reaction process.

The reactor was maintained at a temperature of 63°C for 1 hour. Mixing and circulation were carried out in the reactor so that the solution became homogeneous. The amount of electricity needed for the transesterification process at the pilot plant is 17.49 kWh/ton of biodiesel. After the glycerol solution is separated from the biodiesel, it is then entered into the washing column (2 times) but with the same washing column for 30 minutes. The washing process uses hot water (70°C), to remove impurities or impurities.

Then settling is done again, to separate the biodiesel solution. The next step is to enter the vacuum dryer at a temperature of 90°C, pressure of 70 cmHg for 1-2 hours, to reduce the water content before being stored in the tank. To filter out impurities that are still carried in the biodiesel solution, filtering is needed. The filter used is installed on the pipe so that the biodiesel that is flowed at the same time undergoes filtration.

The final biodiesel product comes out at a temperature of around 40-50°C and the biodiesel is then transferred to storage. Meanwhile, glycerol is separated from the bottom of the reactor. An important by-product in the biodiesel conversion stage is glycerol, which finds various industrial applications (Ciriminna et al., 2014). The sodium hydroxide catalyst will become waste to glycerol, so treatment is needed if the glycerol is to be used. However, unprocessed glycerol cannot be used for the pharmaceutical, cosmetic and tobacco industries because it contains high levels of impurities, free fatty acids and salts, so it requires an expensive purification process.

3.3 Analyzing the environmental impact of biodiesel production from cpo which includes Co_2 emissions (eq), acidification, and eutrophication

3.3.1 CO_2 emissions (eq)

In essence, solar energy reaching the Earth's atmosphere and subsequently leaving it (such as through reflection and infrared radiation) maintains a stable atmospheric temperature. Out of the sunlight reaching the Earth's atmosphere, a fraction (28%) is immediately reflected back into space by air molecules, clouds, and the Earth's surfaces, a phenomenon known as albedo (Bais et al., 2015). The remaining sunlight is divided, with 21% absorbed by greenhouse gases (GHGs) in the atmosphere and 50% by the Earth's surface (Hauschild, 2018). This absorbed energy warms the planet's surface, which emits it back as infrared radiation of longer wavelengths. GHGs partially absorb this radiation, trapping it in the atmosphere and leading to a rise in atmospheric temperature as GHG concentrations increase. According to IPCC data (2013), nitrous oxide (N_2O) has a significantly greater warming potential compared to carbon dioxide (CO_2), with its impact on global warming estimated to be 298 times that of CO_2.

The global warming potential of the biodiesel production life cycle stages is shown in. Total CO_2 emissions (eq) for 1 ton of biodiesel production are 1489 Kg CO_2 (eq) of which 26% comes from the plantation stage, 53% from CPO production and 21% from the biodiesel process. In the plantation phase, NPK fertilizer emissions have a very large contribution of 22.7%. Meanwhile, the transportation sector from plantations to palm oil mills contributed 2.8%. Apart from fertilizer, plants also need pesticides and herbicides for the growth of oil palm plants. The application of herbicides contributes to CO_2 emissions (eq) by 0.17%, whereas the contribution of pesticides is negligible, at 0.01%.

POME waste from palm oil will produce methane emissions so that it will contribute to GHG emissions of 768.6 Kg CO_2 (eq). And the use of diesel oil in the boiler contributes 14.7 Kg CO_2 (eq), because diesel oil is used when starting up the boiler to produce steam. In the biodiesel process, the transesterification process stage makes a significant contribution, especially the use of methanol with a contribution to CO_2 emissions (eq) of 18.4% or 257 Kg CO_2 (eq). The relatively long distance traveled by vehicles between the CPO storage and the Lemigas KESDM biodiesel pilot plant causes high consumption of diesel oil for transportation and the combustion of diesel oil produces emissions of 14.6 Kg CO_2 (eq) or 1.04% of the total emissions from biodiesel production. And the electricity consumed at the Cikasungka palm oil mill and the Lemigas biodiesel pilot plant contributes a small amount to emissions of 0.21 Kg CO_2 (eq) or 0.02%.

3.3.2 Eutrophication

Eutrophication manifests as a noticeable decline in water quality in lakes, rivers, and coastal waters, characterized by reduced visibility and an abundance of surface algae. It results from nutrient enrichment, leading to increased algal biomass, alterations in zooplankton and ecosystem species composition, and deterioration in water quality attributes such as color, odor, and taste. Eutrophication also reduces dissolved oxygen levels, which can lead to biodiversity loss among aquatic plants and animals. In many lakes, phosphorus deficiency typically limits growth, whereas phosphorus addition enhances algal proliferation. Conversely, nitrogen often limits growth in coastal and marine waters. Thus, substances containing bioavailable forms of nitrogen or phosphorus are identified as potential contributors to nutrient enrichment.

The total impact of eutrophication on biodiesel production is 1.12 Kg PO43- (eq), the plantation stage contributes 66%, the CPO production stage 9% and the biodiesel production stage 25%. The plantation stage significantly contributes to eutrophication, primarily due to the application of inorganic fertilizers, particularly NPK fertilizers. These fertilizers release substantial amounts of phosphorus and nitrogen, primarily in the form of phosphate and nitrate, which are major contributors to nutrient enrichment in aquatic ecosystems. And affects ground water and surface water through runoff and ammonia released into the air.

3.3.3 Acidification

Acidification occurs naturally over time but is significantly accelerated by human activities such as agriculture and industry, which introduce hydrogen ions into the soil and vegetation. The primary source of these hydrogen ions is airborne gas emissions that release hydrogen upon degradation in the atmosphere or upon deposition onto soil, vegetation, or water surfaces. This deposition intensifies during precipitation events, where gases dissolve in water and fall as acidic rain, potentially lowering pH values to 3-4 in cases of severe air pollution, commonly known as "acid rain". According to the CML (Institute of Environmental Sciences) impact assessment, the most significant acidifying compounds are sulfur oxides (SO_2 and SO_3, collectively referred to as SO_x), which include sulfur dioxide (SO_2), sulfur trioxide (SO_3), sulfuric acid (H_2SO_4), and sulfurous acid (H_2SO_3). Additionally, nitrogen oxides (NO and NO_2, collectively referred to as NO_x) are also significant contributors, as they can oxidize to form nitric acid in the troposphere (Guinée et al., 2016).

Acidification potential, quantified in terms of SO_2 equivalent, is a measure of the potential environmental impact of processes or products that release acidic substances into the atmosphere. In the context of biodiesel production, the total acidification potential is reported to be 3.06 Kg SO_2 equivalent. The high acidification potential during the plantation stage is attributed to the heavy use of fertilizers, which not only supply essential nutrients to the plants but also result in significant emissions of ammonia. Ammonia, when released into the atmosphere, reacts with other compounds to form acidic substances, thereby contributing to the overall acidification potential. Additionally, in the referenced material likely illustrates the cumulative impact of emissions from all stages of the biodiesel production life cycle, providing a visual representation of how each stage contributes to the total acidification potential.

Acidification, resulting from emissions of acidifying compounds, is primarily a regional phenomenon with effects concentrated around the emission source. When these compounds settle on plant surfaces, they can harm essential plant organs, leading to direct damage. Furthermore, when acidifying compounds infiltrate the soil, they release protons that lower the soil pH and increase the availability of bound metal ions, which can be detrimental to plant health and growth (Yadav et al., 2020). This soil acidification can damage plant roots and leaves, and prolonged exposure to such conditions can ultimately result in plant death.

4. Conclusion

Some conclusions that can be a formulated from this research are: LCI (Life Cycle Inventory) in this research includes. LCI for fresh fruit bunch production of 5.67 tonnes consisting of 141.1 Kg of NPK fertilizer; herbicide (0.25 Kg), water used (1570 m^3), and 0.41 liter diesel oil. LCI CPO production of 1.17 tonnes consisting of fresh fruit bunches of 5.67 tonnes; electricity (16.31 kWh), water (5.2 m^3), and diesel oil (12.43 liters), and POME produced was 3.47 m^3. LCI for biodiesel production in 1 ton consists of CPO of 1.17 tons, electricity (17.49 kWh), diesel oil (15.64 liters), methanol (0.41 tons), and Sodium Hydroxide of 0.01 tons.

The total CO_2 emissions (eq) of biodiesel production from palm oil are 1489 Kg CO_2 (eq), eutrophication is 1.12 Kg PO43- (eq) and acidification is 3.06 Kg SO_2 (eq). With the largest contribution of CO_2 emissions (eq) to CPO production, and the largest contribution of eutrophication and acidification to the production of Fresh Fruit Bunches. The life cycle concept of biodiesel production can be applied with the best alternative for utilizing POME

(Palm Oil Mill Effluent) waste with a priority weighting of 0.357 and a CO_2 emission criterion (eq) of 0.494. From optimizing the life cycle of biodiesel production by utilizing POME, the potential for reducing emissions is 667.2 Kg CO_2 (eq).

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Author Contributio
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References
Ali, H. S., Nathaniel, S. P., Uzuner, G., Bekun, F. V., & Sarkodie, S. A. (2020). Trivariate modelling of the nexus between electricity consumption, urbanization and economic growth in Nigeria: fresh insights from Maki Cointegration and causality tests. *Heliyon*, *6*(2), 1-9. https://doi.org/10.1016/j.heliyon.2020.e03400

Alola, A. A., Bekun, F. V., & Sarkodie, S. A. (2019). Dynamic impact of trade policy, economic growth, fertility rate, renewable and non-renewable energy consumption on ecological footprint in Europe. *Science of the Total Environment*, *685*, 702–709. https://doi.org/10.1016/j.scitotenv.2019.05.139

Ayompe, L. M., Schaafsma, M., & Egoh, B. N. (2021). Towards sustainable palm oil production: The positive and negative impacts on ecosystem services and human wellbeing. *Journal of Cleaner Production*, *278*, 12. https://doi.org/10.1016/j.jclepro.2020.123914

Bekun, F. V., Alola, A. A., & Sarkodie, S. A. (2019). Toward a sustainable environment: Nexus between CO_2 emissions, resource rent, renewable and nonrenewable energy in 16-EU countries. *Science of the Total Environment*, *657*, 1023–1029. https://doi.org/10.1016/j.scitotenv.2018.12.104

Bórawski, P., Bełdycka-Bórawska, A., Szymańska, E. J., Jankowski, K. J., Dubis, B., & Dunn, J. W. (2019). Development of renewable energy sources market and biofuels in The European Union. *Journal of Cleaner Production*, *228*, 467–484. https://doi.org/10.1016/j.jclepro.2019.04.242

Correa, D. F., Beyer, H. L., Fargione, J. E., Hill, J. D., Possingham, H. P., Thomas- Hall, S. R., & Schenk, P. M. (2019). Towards the implementation of sustainable biofuel production systems. *Renewable and Sustainable Energy Reviews*, *107*, 250–263. https://doi.org/10.1016/j.rser.2019.03.005

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). https://doi.org/10.1016/j.seta.2020.100774

Danish, Baloch, M. A., Mahmood, N., & Zhang, J. W. (2019). Effect of natural resources, renewable energy and economic development on CO 2 emissions in BRICS countries. *Science of the Total Environment*, *678*, 632–638. https://doi.org/10.1016/j.scitotenv.2019.05.028

Darda, S., Papalas, T., & Zabaniotou, A. (2019). Biofuels journey in Europe: Currently the way to low carbon economy sustainability is still a challenge. *Journal of Cleaner Production*, *208*, 575–588. https://doi.org/10.1016/j.jclepro.2018.10.147

Dey, S., Reang, N. M., Das, P. K., & Deb, M. (2020). A comprehensive study on prospects of economy, environment, and efficiency of palm oil biodiesel as a renewable fuel. *Journal of Cleaner Production*, 286. https://doi.org/10.1016/j.jclepro.2020.124981

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

FAO. (2020). Oilseeds, Oils & Meals - Monthly Price And Policy Update (No. 126). Fukuda, H., Kondo, A., & Noda, H. (2001). Biodiesel fuel production by transesterification of oils. *Journal of Bioscience and Bioengineering*, *92*(5), 405–416. https://doi.org/10.1016/S1389-1723(01)80288-7

Furumo, P. R., Rueda, X., Rodríguez, J. S., & Ramos, P. I. K. (2020). Field evidence for positive certification outcomes on oil palm smallholder management practices in Colombia. Journal of Cleaner Production, *245*. https://doi.org/10.1016/j.jclepro.2019.118891

Ghazali, A., & Ali, G. (2019). Investigation of key contributors of CO_2 emissions in extended STIRPAT model for newly industrialized countries: A dynamic common correlated estimator (DCCE) approach. *Energy Reports*, *5*, 242–252. https://doi.org/10.1016/j.egyr.2019.02.006

Giannetti, B. F., Agostinho, F., Eras, J. J. C., Yang, Z., & Almeida, C. M. V. B. (2020). Cleaner production for achieving the sustainable development goals. *Journal of Cleaner Production*, *271*. https://doi.org/10.1016/j.jclepro.2020.122127

Ilham, Z., & Nimme, F. H. (2019). Quantitative priority estimation model for evaluation of various non-edible plant oils as potential biodiesel feedstock. *AIMS Agriculturen and Food*, *4*(2), 303–319. https://doi.org/10.3934/AGRFOOD.2019.2.303

Jamaludin, N. F., Muis, Z. A., & Hashim, H. (2019). An integrated carbon footprint accounting and sustainability index for palm oil mills. *Journal of Cleaner Production, 225*, 496–509. https://doi.org/10.1016/j.jclepro.2019.03.312

Leijten, F., Sim, S., King, H., & Verburg, P. H. (2020). Which forests could be protected by corporate zero deforestation commitments? A spatial assessment. *Environmental Research Letters*, *15*(6). https://doi.org/10.1088/1748- 9326/ab8158

Ma, X., Wang, C., Dong, B., Gu, G., Chen, R., Li, Y., Zou, H., Zhang, W., & Li, Q. (2019). Carbon emissions from energy consumption in China: Its measurement and driving factors.

Science of the Total Environment, *648*(27), 1411–1420. https://doi.org/10.1016/j.scitotenv.2018.08.183

Mutsaers, H. J. W. (2019). The challenge of the oil palm: Using degraded land for its cultivation. *Outlook on Agriculture,* *48*(3), 190–197. https://doi.org/10.1177/0030727019858720

Nathaniel, S. P. (2020). Ecological footprint, energy use, trade, and urbanization linkage in Indonesia*. GeoJournal, 7*. https://doi.org/10.1007/s10708-020- 10175-7

Nathaniel, S. P., & Bekun, F. V. (2020). Environmental management amidst energy use, urbanization, trade openness, and deforestation: The Nigerian experience. *Journal of Public Affairs*, *20*(2). https://doi.org/10.1002/pa.2037

Nathaniel, S. P., & Iheonu, C. O. (2019). Carbon dioxide abatement in Africa: The role of renewable and non-renewable energy consumption. *Science of the Total Environment, 679*, 337–345. https://doi.org/10.1016/j.scitotenv.2019.05.011

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

Popovich, C. A., Pistonesi, M., Hegel, P., Constenla, D., Bielsa, G. B., Martín, L. A., Damiani, M. C., & Leonardi, P. I. (2019). Unconventional alternative biofuels: Quality assessment of biodiesel and its blends from marine diatom Navicula cincta. *Algal Research, 39*. https://doi.org/10.1016/j.algal.2019.101438

Sambodo, M. T., & Novandra, R. (2019). The state of energy poverty in Indonesia and its impact on welfare. *Energy Policy,* *132*, 113–121. https://doi.org/10.1016/j.enpol.2019.05.029

Şanli, B. G., Uludamar, E., & Özcanli, M. (2019). Evaluation of energetic-exergetic and sustainability parameters of biodiesel fuels produced from palm oil and opium poppy oil as alternative fuels in diesel engines. *Fuel, 258*. https://doi.org/10.1016/j.fuel.2019.116116

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.* https://doi.org/10.1016/j.landusepol.2019.104073

Santika, W. G., Anisuzzaman, M., Simsek, Y., Bahri, P. A., Shafiullah, G. M., & Urmee, T. (2020). Implications of the Sustainable Development Goals on national energy demand: The case of Indonesia. *Energy, 196*. https://doi.org/10.1016/j.energy.2020.117100

Schröder, P., Antonarakis, A. S., Brauer, J., Conteh, A., Kohsaka, R., Uchiyama, Y., & Pacheco, P. (2019). SDG 12: Responsible Consumption and Production – Potential Benefits and Impacts on Forests and Livelihoods. *In Sustainable Development Goals: Their Impacts on Forests and People*. https://doi.org/10.1017/9781108765015.014

Shahbaz, M., Balsalobre-Lorente, D., & Sinha, A. (2019). Foreign direct Investment–CO 2 emissions nexus in Middle East and North African countries: Importance of biomass energy consumption. *Journal of Cleaner Production, 217*, 603–614. https://doi.org/10.1016/j.jclepro.2019.01.282

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, 190*. https://doi.org/10.1051/e3sconf/202019000021

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

Tan, Y. D., & Lim, J. S. (2019). Feasibility of palm oil mill effluent elimination towards sustainable Malaysian palm oil industry. *Renewable and Sustainable Energy Reviews*, 111, 507–522. https://doi.org/10.1016/j.rser.2019.05.043

Viere, T. (2019). State of the Art and Future Developments in LCA. In Sustainable Production, Life Cycle Engineering and Management. *Springer International Publishing*. https://doi.org/10.1007/978-3-319-92237-9_1

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

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

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