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Environmental and Socio-Economic Impacts of Crude Palm Oil and Kernel Production

Dian Kristina[1]*, Feri Afrinaldi[1], Nilda Tri Putri[1]

ABSTRACT

Palm oil is one of Indonesia's top commodities, but its production faces sustainability concerns, particularly regarding greenhouse gas (GHG) emissions. This study assessed the environmental and socio-economic impacts of Crude Palm Oil (CPO) and kernel production at Palm Oil Mill X using an integrated approach. The Life Cycle Assessment (LCA) method with SimaPro software was used to evaluate 11 environmental impact categories, while socio-economic contributions were analyzed through the Economic Input-Output (EIO) model based on Riau Province's IO table. The results showed that the Global Warming Potential (GWP) reached 556.31 kg CO_2 eq/ton CPO, with 80% from POME. In socio-economic terms, the wage multiplier was 0.930 and the tax multiplier 0.0698, with a total contribution of Rp 23,728,407/ton CPO. The eco-efficiency value for GWP was 2.34×10^{-5} kg CO_2 eq/Rp, highlighting opportunities to reduce emissions through cleaner energy. This research supports sustainability through integrated environmental and economic analysis.

Keywords
Eco-efficiency Analysis, Economic Input Output, Life cycle assessment, Sustainable Development Goals, Palm Oil

[1] Department of Industrial Engineering, Faculty of Engineering, Universitas Andalas
Limau Manis, Pauh, Padang, West Sumatra

* Corresponding Author: diankristina09@gmail.com

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INTRODUCTION

The rapid growth of industry has increasingly drawn attention to sustainability issues in efforts to preserve the environment and ensure the survival of living beings. The Sustainable Development Goals (SDGs) 2030 serve as a transformative global agenda, adopted by all United Nations (UN) member states in 2015, with the aim of comprehensively addressing global challenges and creating a better world for future generations [1]. One of the commodities that has become a major global concern is palm oil, particularly in Indonesia, as the country is the world's largest producer of palm oil. According to the United States Department of Agriculture (USDA) 2022, Indonesia was able to supply 59.7% of global palm oil demand [2]. However, the high export volume of Indonesian palm oil has been accompanied by negative issues, especially concerning the sustainability of palm oil production, which is closely linked to the implementation of various international standards on greenhouse gas (GHG) emission reduction.

According to the United States statement in 2020, biodiesel derived from Indonesian palm oil had not yet met the minimum requirement of a 20% GHG reduction to be categorized as an environmentally friendly product. In line with this, the European Union, through the Renewable Energy Directive (EU RED), established a stricter requirement of at least a 35% GHG reduction, which Indonesian biodiesel was also unable to fulfill [3]. In response, Indonesia implemented various certification schemes, such as the Indonesian Sustainable Palm Oil Certification System (ISPO), the Roundtable on Sustainable Palm Oil (RSPO) standard [4], and the International Sustainability and Carbon Certification (ISCC). Specifically, the ISCC certification has served as an essential instrument for plantation companies in Indonesia to access the European biofuel market [5].

To identify the magnitude of environmental impacts generated from CPO production, this study analyzed both environmental and socio-economic impacts of the production process at Palm Oil Mill (PKS) X, located in Kampar Regency, Riau. PKS X had a production capacity of 60 tons/hour, with CPO and kernel as the main products, while the by-products were empty fruit bunches and Palm Oil Mill Effluent (POME). The focus of this study was to assess the environmental impacts of the 2022 production process and to evaluate the regional socio-economic values using the input-output (I-O) table of Riau Province. The I-O table is an analytical framework that describes the flow of goods and services between different sectors of the regional economy, allowing the identification of production activities in sector [6]. The palm oil milling sector both affects and is interconnected with other sectors. , affect and are linked to other sectors. By applying this framework, the study was able to capture the direct and indirect socio-economic contributions of Palm Oil Mill X (PKS X) to the local economy. The study examined five process units, namely the CPO processing unit, kernel processing unit, boiler unit, water treatment plant (WTP) unit, and engine room unit, thereby enabling the identification of improvements and efficiency measures in the core processes more specifically. The emissions generated by palm oil mills vary due to differences in energy consumption, raw material inputs, and other operational factors, making it difficult to establish generalized conclusions. Consequently, this study concentrated on PKS X to conduct a comprehensive evaluation of the environmental impacts associated with CPO and kernel production processes within the context of its specific operational conditions.

The novelty of this study lay in the integration of sustainability dimensions from both environmental and socio-economic perspectives. The combination of environmental and socio-economic impacts aimed to obtain the eco-efficiency value in the CPO and kernel production process at PKS X Riau. The integration of these assessments generated a single value representing a composite indicator of environmental impacts and a composite indicator of socio-economic impacts. The methodological framework developed in this study provided a more measurable approach to assessing sustainability and had the potential to serve as a reference for the development of similar studies in the future.

Accordingly, this study aimed to quantify the environmental impacts and socio-economic contributions of CPO and kernel production processes at PKS X Riau by applying the Life Cycle Assessment (LCA) method and the Economic Input-Output (EIO) model, and to integrate these dimensions into an eco-efficiency analysis that reflects the balance between environmental burdens and socio-economic benefits.

METHOD

This study measures the environmental impact value generated per Rupiah unit during the production processes of Crude Palm Oil (CPO) and kernel at Palm Oil Mill X in Riau by combining environmental impacts and socio-economic impacts to obtain a single, measurable aggregate value through eco-efficiency analysis. The environmental impact assessment was conducted using the Life Cycle Assessment (LCA) method with the assistance of SimaPro 9.6.1 software, employing the CML-Baseline 2000 method. The LCA method enables a systematic evaluation of environmental impacts associated with all stages of the production process, from the use of raw materials and energy to waste generation and emissions. The CML-Baseline 2000 method was selected because it provides a standardized approach for classifying and characterizing environmental impacts into key categories, such as global warming potential, acidification, eutrophication, and resource depletion, thereby ensuring comprehensive and comparable results [7][8][9]. The socio-economic impact assessment utilized the Economic Input-Output method based on the Input-Output (IO) Table of Riau Province [10]. The environmental impact assessment comprised 11 categories of environmental impacts, including abiotic depletion, abiotic depletion (fossil fuels), GWP, ozone depletion potential (ODP), human toxicity, ecotoxicity (aquatic), ecotoxicity (marine), ecotoxicity (terrestrial), photochemical oxidation, acidification, and eutrophication [11].

Data Collection

Data were collected through direct observation and quantitative measurements to gain a comprehensive understanding of the production process flow and the utilization of materials and energy within the mill. Direct observations were carried out systematically across all major process units to document operational activities, equipment performance, and material flow patterns. Quantitative data referred to measurable numerical information that could be statistically analyzed to evaluate production efficiency and environmental performance. The primary data considered were historical records from 2022, including detailed production volumes of CPO and kernel, the quantities of raw materials and chemicals used, energy consumption data for electricity and fuel, as well as records of waste and emissions generated. These data were supplemented by on-site measurements where necessary to ensure completeness and accuracy. Secondary data for assessing socio-economic values were obtained from the input-output table based on data published by the Central Statistics Agency (BPS) of Riau Province in 2016, which were adjusted to reflect the 2021 budget. This table included a classification of 15 relevant economic sectors and two primary inputs (wages and taxes) directly related to palm oil production, enabling a comprehensive evaluation of the sector's economic linkages [10].

The literature review was conducted by collecting data from previous studies and consulting with experts in the relevant field. This review was aimed at strengthening the research framework and validating the findings.

Data Processing

Data processing in this study was conducted through the following stages and also illustrated in Figure 1:

1. Environmental Impact Assessment

The analysis of environmental impacts was carried out using the Life Cycle Assessment (LCA) method, which consisted of four main stages: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [12].

a. Goal and scope definition

In the goal and scope definition stage, the boundaries of the study were established, focusing on the production processes of CPO and kernel at Palm Oil Mill X. This included identifying the functional unit, which was defined as one ton of processed fresh fruit bunches (FFB).

b. Life Cycle Inventory

The LCI analysis stage involved the systematic collection and quantification of all input and output data, including raw materials, energy consumption, water usage, and waste streams generated across each process unit. Data were collected through direct observation, historical production records, and on-site measurements to ensure accuracy and completeness.

c. Life Cycle Impact Assessment
During the LCIA stage, the collected inventory data were analyzed using SimaPro 9.6.1 software with the CML-Baseline 2000 method to categorize environmental impacts into key indicators such as global warming potential, acidification, eutrophication, resource depletion and impact others.

d. Interpretation
The results were evaluated to identify critical processes contributing most significantly to environmental impacts, enabling recommendations for improvement and mitigation measures.

2. Socio-Economic Impact Assessment

This assessment was conducted using the Economic Input-Output (EIO) method. The integration of life cycle assessment and economic input-output analysis was based on the work of Leontief in the 1930s [13]. The process began with the identification of relevant sectors linked to the palm oil production system. Data were obtained from the Central Statistics Agency (BPS) of Riau Province, using the 2016 input-output table adjusted to reflect the 2021 economic structure and budget. From this dataset, 15 related sectors were identified, along with two primary socio-economic factors, namely wages and taxes. The EIO calculation stage involved processing these data to trace both direct and indirect economic contributions of CPO and kernel production. This allowed the measurement of economic linkages, including the multiplier effects of palm oil production on other sectors of the regional economy. The output of this stage was a comprehensive set of socio-economic values that represent the overall contribution of palm oil milling activities to the local economy. The EIO calculation and analysis were carried out in accordance with the research framework and stages proposed in previous sectoral studies conducted in Indonesia [14].

3. Eco-Efficiency Analysis

This measurement was performed using the eco-efficiency analysis method, by combining environmental impact values with socio-economic impact values. The environmental impacts were divided by the socio-economic contributions to generate an aggregated value, enabling the analysis of the relationship between socio-economic benefits and environmental performance. In the first step, the total environmental impact values derived from the LCA were compiled for each impact category. These values were subsequently integrated with the corresponding sectoral socio-economic contribution data derived from the EIO analysis. The final step involves calculating the environmental efficiency ratio, where environmental impact is divided by socio-economic benefits. A lower ratio indicates higher environmental efficiency, meaning greater socio-economic benefits are achieved with a lower environmental burden.

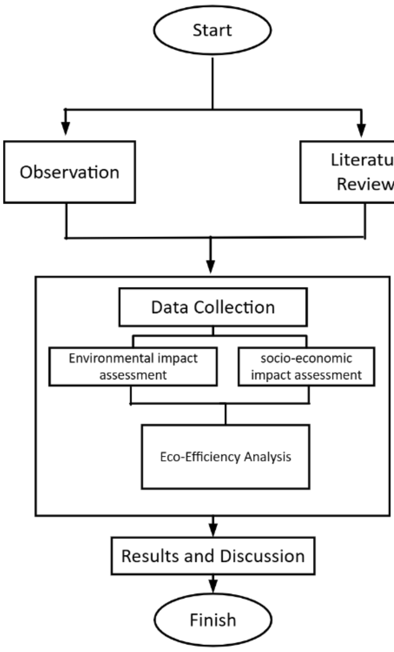

Figure 1. Research Flowchart

RESULT AND DISCUSSION

Environmental Impact Assessment

The environmental impacts were evaluated through a Life Cycle Assessment (LCA) using SimaPro software version 9.6.1 and the CML-IA Baseline 2000 method. The analysis followed ISO 14044 standards [15] to assess the production processes of crude palm oil (CPO) and palm kernel. The system boundary was defined as gate-to-gate, as illustrated in Figure 2.

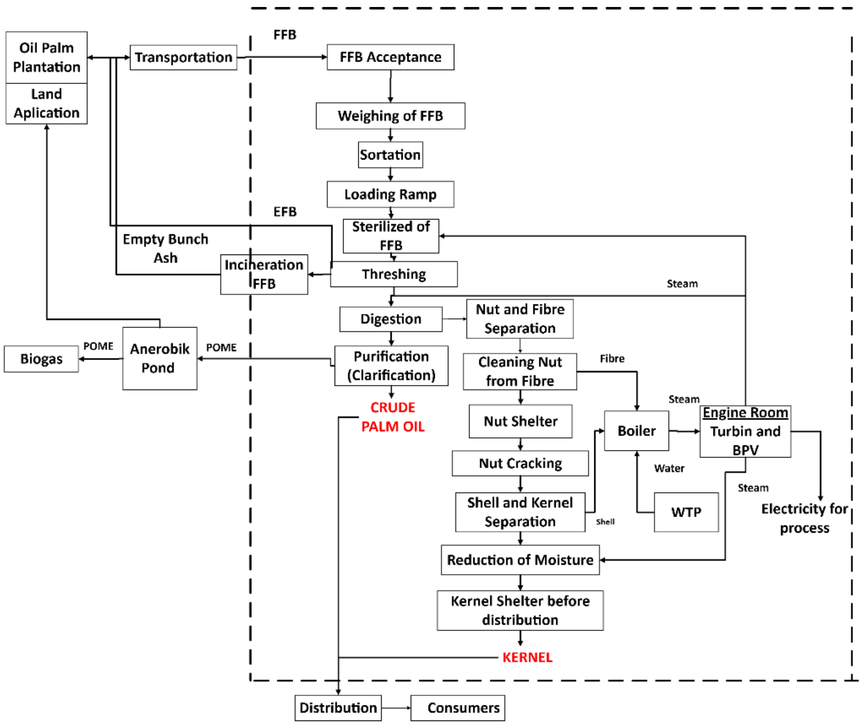

Figure 2. Scope Gate to Gate

The functional unit in this study was defined as 1 ton of CPO, representing the quantity of inputs in terms of raw materials, materials, and energy consumed throughout the life cycle of CPO and kernel production processes. In the Life Cycle Impact Assessment stage, information from the inventory data was compiled and complemented with measurement coefficients of emissions or absorption per unit of activity, known as emission factors (EF). All numerical data were entered into SimaPro, where calculations were performed automatically using the selected database, resulting in a single aggregated value of environmental impact.

The outcomes of the environmental impact assessment across eleven categories are summarized in Table 1.

Table 1. Result of Environmental Impact Assessment

Impact Category	Results of Environmental Impact Assessment
Abiotic depletion (Kg SB eq/Ton CPO)	5,21E-04
Abiotic depletion (*Fossil fuels*) (MJ/Ton CPO)	1,48E+02
Global warming (GWP100a) (kg CO_2 eq/Ton CPO)	5,56,E+02
ODP (Kg CFC-11 eq/Ton CPO)	3,08E-06
Human toxicity (kg 1,4-DB eq/Ton CPO)	2,03E+02
Ecotoxicity (aquatic) (kg 1,4-DB eq/Ton CPO)	1,06E+02
Ecotoxicity (marine) (kg 1,4-DB eq/Ton CPO)	1,22E+05
Ecotoxicity (terrestrial) (kg 1,4-DB eq/Ton CPO)	2,31E+01
Photochemical oxidation (kg C_2H_4 eq/Ton CPO)	2,18E-02
Acidification (kg SO_2 eq/Ton CPO)	9,63E-01
Eutrophication (kg PO_4^{3-}eq/Ton CPO)	8,16E-01

Based on Table 1, the abiotic depletion value was 5.21×10^{-4} kg Sb eq/ton CPO, which differed from the findings and reported a higher value of 1.10×10^{-1} kg Sb eq/ton CPO [16]. This difference was attributed to variations in the technology employed as well as differences in the quantity of inventory data. Both studies, however, utilized biomass from empty fruit bunch waste as boiler fuel for electricity generation. The abiotic depletion – fossil fuels value was 147.64 MJ/ton CPO, originating from the use of fuels and lubricants such as diesel engine oil, grease, and lubricating oil. By [17] reported a lower value of 90 MJ. In this study, diesel engine oil consumption was associated with its use as fuel for transportation (loaders) and for diesel engines in the engine room unit, leading to differences in material usage.

The GWP was 556.31 kg CO_2 eq/ton CPO, which contrasted with the study by [18], who analyzed 14 palm oil mills in Thailand and reported an average GWP of 1,198 kg CO_2 eq/MT CPO, with the lowest value recorded at 626 kg CO_2 eq/MT CPO. Their study included biogas treatment, unlike the case of PKS X in this study. At PKS X, approximately 80% of the GWP contribution originated from the CPO processing unit, particularly from Palm Oil Mill Effluent (POME) that generated methane gas. This finding aligned with[19][20], who noted that around 65% of methane (CH_4) emissions from POME significantly impacted the environment. By [21] further emphasized that in life cycle analysis, CO_2 emissions from electricity, primarily sourced from fossil fuels, play an important role in the GWP of the palm oil industry [22].

This study yielded an Ozone Depletion Potential (ODP) of 3.08×10^{-6} kg CFC-11 eq/ton CPO, which differs from the findings of [17], who reported a lower value of 8.95×10^{-11} kg CFC-11 eq/ton CPO. This difference in values may be attributed to the varying amounts of chemicals used, depending on the specific industry. Emissions of CFC/HCFC arise from organic solvent chemicals [21]. The human toxicity value, which can impact the health of individuals in the vicinity of the industry, was found to be 203 kg 1,4-DB eq/ton CPO in this study. This aligns with the work of [23], where human toxicity potential is calculated based on the hazard level per unit of chemical released into the environment, determined by the toxicity characteristics of the compounds and their doses. Ecotoxicity impacts are caused by toxic compounds such as HCl released into the environment through liquid waste and chemicals, which subsequently affect organisms across various ecosystems, including terrestrial, freshwater, and marine environments [23]. The ecotoxicity impact on marine ecosystems was recorded to be higher than that on freshwater ecosystems. This condition is suspected to be due to the lower tolerance range of marine organisms to the chemicals produced during the production process, making them more vulnerable to pollution compared to freshwater organisms, which tend to have better adaptive capabilities.

The photochemical oxidation impact was calculated at 2.18×10^{-2} kg C_2H_4 eq/ton CPO, which is lower than the value reported by [16], namely 1.32×10^{-1} kg C_2H_4 eq/ton CPO. Photochemical oxidation in CPO production is primarily driven by emissions of volatile organic compounds (VOCs) generated during the oil extraction and refining processes, further exacerbated by additional emissions from fossil fuel combustion was found to be 9.63×10^{-1} kg SO_2 eq/ton CPO, which is higher than the value reported by [7], namely 2.58×10^{-2} kg SO_2 eq/ton CPO. This discrepancy can be attributed to fuel consumption and acidifying emissions derived from palm oil mill effluent (POME) and empty fruit bunches (EFB). This finding is consistent with [24], who emphasized that NO_x and SO_2 emissions from fossil fuel combustion are the main contributors to acidification in the CPO industry.The eutrophication potential was calculated at 8.16×10^{-1} kg $PO_4{}^{3-}$ eq/ton CPO, which is higher than the 0.64 kg $PO_4{}^{3-}$ eq/ton CPO [25]. The utilization of renewable energy sources combined with the implementation of advanced wastewater treatment systems has been shown to significantly reduce eutrophication impacts [25].

In general, variations in environmental impact values can be explained by differences in production capacity, technological configurations, research scope, levels of material and energy consumption, as well as the types and quantities of outputs released into the environment.

Socio-Economic Impact Assessment

This study integrates social and economic aspects to measure the contribution of value added derived from wage compensation and taxation in palm oil production. The added value contribution, representing a combination of social and economic dimensions. This concept suggests that faster economic growth, accompanied by increased employment opportunities, drives economic welfare, which in turn facilitates the expansion of essential social services such as education, social security, and healthcare [26].

The results of the Economic Input-Output (EIO) calculation indicate that labor compensation (wages) reached a multiplier value of 0.930. This implies that every increase of IDR 1 in palm oil demand generates a total increase of IDR 0.930 across 15 related sectors. For the socio-economic aspect of taxation, the calculated value was 0.0698, indicating that tax revenue increases by IDR 0.0698 for every IDR 1 increase in palm oil demand. The higher multiplier value of labor compensation compared to taxation suggests that the palm oil industry plays a significant role in supporting workers' income, which in turn has a positive effect on both local communities and the national economy through increased per capita income.

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The final contribution value, or G(+), of IDR 23,728,407 per ton of CPO represents the magnitude of the economic contribution derived from the production and sale of 1 ton of CPO through wage and tax components. This value is comparable to the selling price of 1 ton of CPO, suggesting that wages and taxes account for a substantial portion of the total revenue, while other production factors are excluded. This finding aligns with [14] that an increase in income value and tax multipliers provides benefits. However, when such an increase is accompanied by a reduction in environmental impacts, the resulting benefits become significantly greater.

Eco-Efficiency Analysis

The measurement of environmental impact (LCA) per rupiah was calculated by dividing the aggregate environmental impact results by the aggregate socio-economic impact results using the Eco-Efficiency Analysis. The environmental impacts were assessed across 11 categories, while the aggregate socio-economic impact value (EIO) was determined to be Rp23,728,407 per ton CPO. Using the Eco-efficiency analysis formula, the results for each impact per rupiah were obtained, with particular emphasis on the GWP due to concerns regarding greenhouse gas emissions. The eco-efficiency value for GWP was found to be 2.34×10^{-5} kg CO_2 eq/Rp, indicating a reduction in emissions through the use of cleaner energy sources.

The aggregate value of environmental impact measurement per rupiah, calculated using eco-efficiency analysis, was based on the environmental impact values generated from each impact category. A smaller impact value corresponds to a lower value per rupiah. The results of the environmental impact measurement per rupiah, along with the eco-efficiency analysis, can be seen in Table 2.

Table 2. Eco-Efficiency Analysis

Impact Category	Results of Eco-Efficiency Analysis
Abiotic depletion (kg SB eq/Rp)	5,21E-04
Abiotic depletion (*Fossil fuels*) (MJ /Rp)	6,22E-05
Global warming (GWP100a) (kg CO_2 eq /Rp)	2,34E-05
ODP (Kg CFC-11 eq /Rp)	1,30E-13
*Human toxicity (*kg 1,4-DB eq /Rp)	8,55E-06
*Ecotoxicity (aquatic) (*kg 1,4-DB eq /Rp)	4,46E-06
Ecotoxicity (Marine) (kg 1,4-DB eq /Rp)	5,13E-03
Ecotoxicity (Terrestrial) (kg 1,4-DB eq /Rp)	9,72E-07
*Photochemical oxidation (*kg C_2H_4 eq /Rp)	9,18E-10
Acidification (kg SO_2 eq/Rp)	4,06E-08
Eutrophication (Kg PO_4^{3-} eq/Rp)	3,44E-08

CONCLUSION

Overall, the results of the environmental impact measurement per rupiah, which combine environmental impact values and socio-economic impact values, yield an eco-efficiency analysis that aligns with several Sustainable Development Goals (SDGs). These include Goal 6 (Clean Water and Sanitation), Goal 7 (Affordable and Clean Energy), Goal 12 (Responsible Consumption and Production), Goal 13 (Climate Action), Goal 14 (Life Below Water), and Goal 15 (Life on Land) for environmental aspects. In terms of socio-economic objectives, the relevant goals are Goal 1 (No Poverty), Goal 2 (Zero Hunger), Goal 3 (Good Health and Well-Being), and Goal 8 (Decent Work and Economic Growth).

This research makes a significant contribution to the development of knowledge by integrating sustainability assessment aspects, specifically environmental impacts using the Life Cycle Assessment (LCA) method and socio-economic impacts using the Economic Input-Output (EIO) method. The values obtained were then analyzed through eco-efficiency analysis to derive the ratio of environmental impact per rupiah. The aggregation of these assessments results in a single representative value, which serves as a singular indicator for environmental impact and a singular indicator for socio-economic impact. The methodology developed in this study offers a more measurable approach to evaluating sustainability and can serve as a reference for similar research in the future. Future studies could combine all aspects of the SDGs within a broader industrial scope, providing a more comprehensive overview.

REFERENCES

[1] M. Sarwani, L. Nurida, and F. Agus, “Isu Emisi Gas Rumah Kaca dan Penggunaan Lahan Sehubungan dengan Pemanfaatan Bioenergi di Indonesia,” *J. Litbang Pert*, vol. 32, no. 2, pp. 56–66, 2013, [Online]. Available: http://en.wikipedia.org/wiki/

[2] S. P. Pareira, “Mencapai Keterlacakan Minyak Sawit Indonesia yang Menyeluruh melalui Harmonisasi ISPO-RSPO,” no. 56, 2023, [Online]. Available: https://repository.cips-indonesia.org/pt/publications/560889/mencapai-keterlacakan-minyak-sawit-indonesia-yang-menyeluruh-melalui-harmonisasi%0Ahttps://repository.cips-indonesia.org/media/publications/560889-mencapai-keterlacakan-minyak-sawit-indon-2b12d7

[3] S. Hasibuan and H. Thaheer, “Life Cycle Impact Assessment Produksi Biodiesel Sawit Untuk Mendukung Keberlanjutan Hilirisasi Industri Sawit Indonesia,” *Semin. Nas. Inov. Dan Apl. Teknol. Di Ind. 2017 ITN Malang*, pp. 1–7, 2017.

[4] RSPO, “iii RSPO Supply Chain Certification Standard RSPO-STD-T05-001 V2 ENG,” 2020.

[5] ISCC, “ISCC GUIDANCE WASTE AND RESIDUES FROM,” 2024.

[6] A. Armelly, M. Rusdi, and E. Pasaribu, “Analisis sektor unggulan perekonomian Indonesia: Model input-output,” *Sorot*, vol. 16, no. 2, p. 119, 2021, doi: 10.31258/sorot.16.2.119-134.

[7] S. A. Krisi, M. A. Jami’in, and M. Apriani, “Potensi Dampak Lingkungan Pada Industri Minyak Goreng Sawit Dengan Metode Life Cycle Assessment,” *J. Ilmu Lingkung.*, vol. 20, no. 3, pp. 672–677, 2022, doi: 10.14710/jil.20.3.672-677.

[8] Y. Arba and S. Thamrin, “Journal Review: Perbandingan Pemodelan Perangkat Lunak Life Cycle Assessment (LCA) untuk Teknologi Energi,” *J. Energi Baru dan Terbarukan*, vol. 3, no. 2, pp. 142–153, 2022, doi: 10.14710/jebt.2022.14001.

[9] A. P. Iswara *et al.*, “A Comparative Study of Life Cycle Impact Assessment using Different Software Programs,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 506, no. 1, 2020, doi: 10.1088/1755-1315/506/1/012002.

[10] Badan Pusat Statistik, “Input Output Table of Indonesia 2016 (in Bahasa),” 2021, [Online]. Available:

https://www.bps.go.id/id/publication/2021/03/31/081f6b0af2c15c524d72b660/tabel-input---output-indonesia-2016.html
[11] R. Heijungs, J. Guinée, and G. Huppes, *Impact categories for natural resources and land use*, no. Cml. 1997. [Online]. Available: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:IMPACT+CATEGORIES+FOR+NATURAL+RESOURCES+and+Land+Use#0
[12] N. Jungbluth, "Description of life cycle impact assessment methods Supplementary information for tenders," pp. 1–40, 2020, [Online]. Available: my.sharepoint.com/personal/mitarbeiter1_esuservices_onmicrosoft_com/Documents/files/V orlagen/ESU-Description-of-LCIAmethods.docx
[13] W. Leontief, "The economy as a circular flow," *Struct. Chang. Econ. Dyn.*, vol. 2, no. 1, pp. 181–212, 1991, doi: 10.1016/0954-349X(91)90012-H.
[14] F. Afrinaldi, "A new method for measuring eco-efficiency," *Clean. Environ. Syst.*, vol. 7, no. July, p. 100097, 2022, doi: 10.1016/j.cesys.2022.100097.
[15] ISO, "Environmental Management - Life Cycle Assessment - Principles and Framework (ISO 14040:2006)," *Br. Stand.*, vol. 3, no. 1, p. 32, 2004, [Online]. Available: https://www.iso.org/standard/23151.html
[16] A. Hidayatno, T. Y. M. Zagloel, W. W. Purwanto, . C., and L. Anggraini, "Cradle To Gate Simple Life Cycle Assessment of Biodiesel Production in Indonesia," *MAKARA Technol. Ser.*, vol. 15, no. 1, 2011, doi: 10.7454/mst.v15i1.851.
[17] Ahmadi *et al.*, "Cradle to Gate Life Cycle Assessment of Palm Oil Industry," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1143, no. 1, p. 012044, 2021, doi: 10.1088/1757-899x/1143/1/012044.
[18] R. Kaewmai, A. H-Kittikun, and C. Musikavong, "Greenhouse gas emissions of palm oil mills in Thailand," *Int. J. Greenh. Gas Control*, vol. 11, pp. 141–151, 2012, doi: 10.1016/j.ijggc.2012.08.006.
[19] A. Wijono, "Dampak Pengurangan Emisi Gas Rumah Kaca Pada Pemanfaatan POME untuk Pembangkit," *Pros. Semnastek*, no. 1-2 November, pp. 1–9, 2017, [Online]. Available: https://jurnal.umj.ac.id/index.php/semnastek/article/view/1946%0Ahttps://jurnal.umj.ac.id/index.php/semnastek/article/download/1946/1596
[20] D. A. P. Sari, A. Rahmah, and N. A. Sasongko, "Life Cycle Assessment (LCA) in Palm Oil Plantation and Mill with Impact Categories Global Warming Potential, Acidification, and Eutrophication," *Int. J. Membr. Sci. Technol.*, vol. 10, no. 2, pp. 797–807, 2023, doi: 10.15379/ijmst.v10i2.1236.
[21] L. Reijnders and M. A. J. Huijbregts, "Palm oil and the emission of carbon-based greenhouse gases," *J. Clean. Prod.*, vol. 16, no. 4, pp. 477–482, 2008, doi: 10.1016/j.jclepro.2006.07.054.
[22] N. Permpool, A. Mahmood, H. U. Ghani, and S. H. Gheewala, "An eco-efficiency assessment of bio-based diesel substitutes: A case study in Thailand," *Sustain.*, vol. 13, no. 2, pp. 1–10, 2021, doi: 10.3390/su13020576.
[23] A. P. Acero, C. Rodríguez, and A. Ciroth, "LCIA methods," *Impact Assess. methods Life Cycle Assess. their impact Categ.*, pp. 1–23, 2016.
[24] D. A. P. Sari, M. Nikmah, and N. A. Sasongko, "Life Cycle Assessment in the Production Process of Crude Palm Oil (Cpo) on Palm Oil Plantation and Mills," *Int. J. GEOMATE*, vol. 25, no. 111, pp. 177–184, 2023, doi: 10.21660/2023.111.s8616.
[25] N. P. Sari, "Optimasi Leaching Tandan Kosong Kelapa Sawit Sebagai Bahan Baku Biopellet yang Rendah Mineral," no. July, pp. 1–23, 2023.
[26] G. A. Norris, "Social impacts in product life cycles: Towards life cycle attribute assessment," *norris*, vol. 11, no. SPEC. ISS. 1, pp. 97–104, 2006, doi: 10.1065/lca2006.04.017.