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Enhancing Sustainability of Used Cooking Oil-Biodiesel Through Integrated Eco-Efficiency and Eco-Technology Assessment: An Indonesian Case Study

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ABSTRACT

This study evaluates the sustainability performance of biodiesel production from used cooking oil (UCO) through an integrated eco-efficiency and eco-technology assessment framework combining life cycle assessment (LCA) and data envelopment analysis (DEA). A case study was conducted at a medium-scale biodiesel production facility in Indonesia with a functional unit of 950 L of biodiesel. LCA was employed to quantify environmental impacts, while DEA was used to evaluate operational efficiency across 18 decision-making units (DMUs). The results show a total environmental impact of 1.15 mPt, with raw material collection from the Kuta area contributing the highest impact (0.353 mPt), followed by biodiesel distribution to the Ubud area (0.169 mPt). DEA results indicate that only three DMUs achieved full efficiency (efficiency score = 1.00), whereas the remaining units exhibited varying levels of inefficiency primarily caused by excessive potassium hydroxide (55.6%), energy consumption (44.4%), and methanol usage (27.8%). Based on these findings, an eco-technology scenario is proposed to reduce resource consumption and improve environmental and operational performance. The integrated LCA–DEA framework provides practical decision support for enhancing the sustainability of UCO-based biodiesel production in developing countries.

1. INTRODUCTION

Energy security refers to the availability, accessibility, affordability, and environmental sustainability of energy use [1]. It is a critical factor in economic productivity, as disruptions in energy supply can significantly affect the production of goods and services. One key strategy to enhance energy security is the diversification of energy sources to reduce dependence on a single fuel. In this context, biodiesel has emerged as a promising alternative and remains an important component of government energy policies. Its adoption continues to expand globally, supported by increasing international recognition and policy endorsement [2].

However, the government's mandatory biodiesel policy faces significant challenges, particularly in securing supporting materials such as methanol, which is still largely imported [3]. In addition, reliance on crude palm oil as the primary feedstock creates competition with its use in the food sector, requiring careful management. The increasing biodiesel blending mandate is expected to further raise demand for crude palm oil, raising concerns over deforestation, greenhouse gas emissions, biodiversity loss, flooding, and broader socio-ecological impacts that contradict the objective of environmentally sustainable biofuels [4]. Despite these efforts, biodiesel production targets have not yet been achieved, as shown in Figure 1, indicating limitations in current production capacity. Therefore, the biodiesel industry requires alternative feedstock strategies to support the long-term sustainability of the mandatory biodiesel program.

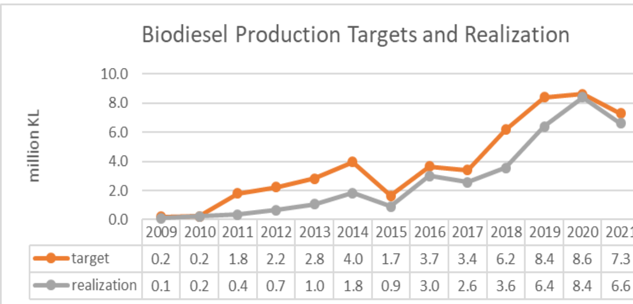

Figure 1. Target and realization of Indonesian biodiesel production

In light of these challenges, exploring alternative feedstocks beyond palm oil is essential. Used cooking oil (UCO) has gained increasing attention as a viable feedstock for biodiesel production and, more recently, sustainable aviation fuel, supporting global efforts to reduce carbon emissions in the transportation sector. Global projections indicate a steady growth in UCO supply, with Asia as the main supplier and Europe as the largest consumer of low-carbon fuels [5]. In Indonesia, UCO is primarily generated from the food sector, including restaurants, hotels, and street vendors; however, its utilization requires pre-treatment to reduce water content and free fatty acids to meet quality standards [6]. UCO is classified as an advanced feedstock because it does not compete with food resources while helping to mitigate environmental impacts from improper waste oil disposal [7]. Therefore, UCO offers significant potential to reduce greenhouse gas emissions, support the circular economy, and enhance energy independence, particularly in developing countries with high cooking oil consumption [5, 8].

According to the International Council on Clean Transportation (ICCT), Indonesia has the potential to produce 157 million liters of UCO from restaurants, hotels, and schools in urban areas, while household sources could reach 1,638 million liters and are expected to increase with rising cooking oil consumption [9]. This indicates that Indonesia has strong potential for the development of UCO-based biodiesel, supported by high consumption and a widespread culinary sector. Despite this potential, a significant portion of UCO is still exported rather than utilized domestically. In contrast, countries such as India have implemented policies to promote UCO utilization through pricing mechanisms and incentives [10]. Therefore, further research is needed to assess the readiness of large-scale UCO utilization for biodiesel production, particularly in terms of process, technology, and environmental performance.

The concept of eco-efficiency serves as an important analytical approach that integrates the goals of reducing environmental impacts while improving economic performance [11]. In the context of UCO-based biodiesel, previous studies have identified electricity and methanol consumption as the main contributors to environmental impacts, highlighting the importance of optimizing these inputs to enhance eco-efficiency [12]. Furthermore, the application of a cradle-to-customer approach has been recommended to evaluate energy efficiency and emissions, supported by sensitivity analysis of factors such as transport distance and raw material variability [13]. In this regard, life cycle assessment (LCA) has been widely applied to evaluate the environmental performance of biodiesel production from UCO, demonstrating its potential to mitigate climate change, although current systems are not yet fully sustainable [14, 15].

Eco-technology refers to the application and development of technologies aimed at conserving resources, reducing emissions, and recovering material value within process systems [16]. It encompasses innovative services, processes, and systems that support economic growth while minimizing environmental impacts [17]. Eco-technology also promotes the use of non-fossil resources to address pollution challenges [18]. Compared to conventional approaches, eco-technology offers advantages in reducing environmental burdens, although it is often associated with higher implementation costs [19]. Therefore, integrating eco-technology with eco-efficiency is essential to achieve both economic and environmental sustainability. While eco-technology has been widely applied in sectors such as water treatment [20], biogas production [21], solar cells [22], and agriculture [23], yet its application in UCO-based biodiesel remains significantly constrained.

In the transition toward a low-carbon economy, the integration of eco-efficiency principles with eco-technology plays a crucial role in reducing resource intensity while improving economic performance. Accordingly, recent research has focused on developing technological frameworks that not only meet biodiesel quality standards but also optimize the ratio of outputs to resource and energy inputs. Previous studies indicate that production profitability is strongly influenced by raw material prices and operational efficiency. Techno-economic assessments further show that production costs are sensitive to pre-treatment processes, as well as methanol and catalyst consumption, while also highlighting opportunities for improving energy utilization [24]. In addition, process intensification, waste recycling, and energy recovery have been identified as effective strategies to enhance the value of UCO-based biodiesel production [25]. Therefore, improving process efficiency through better pretreatment, robust catalysts, and recovery systems remains a key opportunity for sustainable biodiesel development.

This study integrates eco-efficiency and eco-technology within a unified evaluation framework, employing LCA to assess environmental impacts and data envelopment analysis (DEA) to quantify relative efficiency among decision-making units (DMUs). Although its application in UCO-based biodiesel production remains limited, operational data such as energy consumption, chemical use, and emissions reported in previous studies can be used to construct DEA variables for evaluating eco-efficiency [12, 13]. The DEA approach offers several advantages, including the ability to compare efficiency across units, incorporate both environmental and operational indicators, identify improvement strategies, and detect inefficiencies such as wasted energy [26]. This integrated approach is consistent with recent research trends that emphasize the simultaneous evaluation of environmental and economic performance in the biofuel sector [27]. Therefore, this study aims to optimize biodiesel production by integrating eco-efficiency and eco-technology to minimize environmental impacts while improving operational performance. In addition, the study evaluates practical technology options under real operational conditions to support implementation in small- to medium-scale UCO-based biodiesel production systems.

2. MATERIALS AND METHODS

2.1 Case study description

This research was conducted at Lengis Hijau (LH), a medium-scale biodiesel producer in Bali, Indonesia, with an average production capacity of 950 liters per batch. The facility sources UCO primarily from hotels, restaurants, and households (Horeca). The process flow includes raw material collection, pretreatment, transesterification using methanol and potassium hydroxide (KOH), glycerol separation, methanol recovery, and dry washing. The production system also incorporates a local distribution network supplying biodiesel to nearby consumers. This case study was selected due to its representative operational scale and established production system, making it suitable for evaluating real-world biodiesel performance under practical conditions. The stages of the research are illustrated in Figure 2.

2.2 Data collection

Primary data were obtained through on-site observations, process monitoring, and interviews with the production manager, covering material consumption (UCO, methanol, KOH, resin), energy usage (electricity and thermal energy), and transportation distances. Data were collected over a representative production period to ensure consistency and were cross-validated using operational records and interview results. Secondary data were supplemented from scientific literature, governmental reports, and the Ecoinvent v3.8 database to fill gaps, particularly regarding emission factors. The functional unit was defined as 950 liters of UCO-based biodiesel delivered to the end-user.

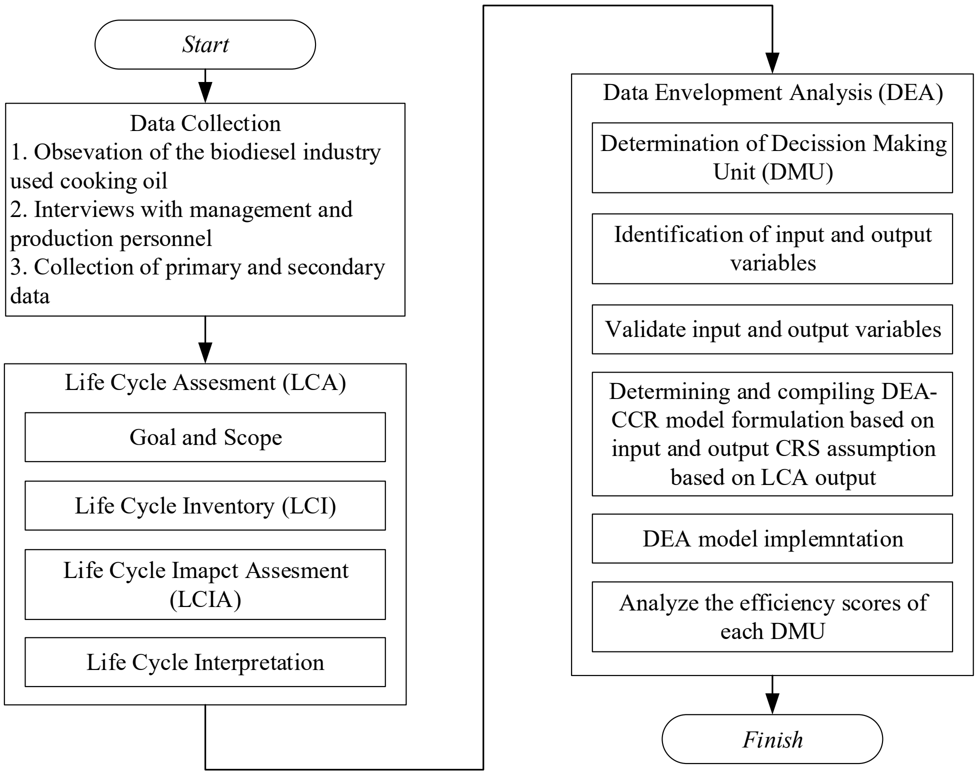

Figure 2. Research flow

Although the functional unit is expressed as 950 L of biodiesel delivered to the end-user, the life cycle inventory (LCI) is reported in kilograms because mass-based units are required for LCA modelling and are consistent with the Ecoinvent database. Therefore, volumetric measurements were converted into mass using the corresponding material densities. For biodiesel, a density of approximately 0.926 kg/L was applied, resulting in an equivalent product mass of approximately 880 kg for the defined functional unit.

2.3 Life cycle assessment

LCA was applied to evaluate the environmental impacts of biodiesel production using a cradle-to-customer system boundary, following ISO 14040 and ISO 14044 standards [28]. The system boundary was defined to reflect actual operational conditions of the case study. The assessed stages included:

a. Raw material collection and transportation.
b. Oil pretreatment and filtration.
c. Transesterification reaction.
d. Methanol recovery and purification.
e. Dry washing and final product distribution.

The LCI included inputs such as UCO, methanol, KOH, resin, electricity, and transport fuel, while outputs comprised biodiesel, glycerol, wastewater, residual methanol, and gaseous emissions (CO_2, NO_x, SO_2, CO, hydrocarbons, particulates). The life cycle impact assessment (LCIA) was conducted using the EDIP 2003 method, covering impact categories including global warming potential, acidification, eutrophication, and ozone depletion. The results were normalized to Person Equivalent (PE) and expressed as a single score (mPt) for interpretation

The stage-level CO_2 emissions reported in the inventory were estimated from the electricity consumption of each production process using the corresponding electricity emission factors implemented in the Ecoinvent v3.8 database. No direct CO_2 emissions from the transesterification reaction were assumed because the reaction primarily produces biodiesel and glycerol without significant direct carbon dioxide generation. Transportation-related emissions were calculated separately based on transport distances and fuel consumption datasets available in the background database.

2.4 Data envelopment analysis

DEA is a quantitative method used to measure relative efficiency among units by analyzing the ratio of inputs to outputs [29]. In this study, DEA was applied to evaluate eco-efficiency across different stages of biodiesel production, with each decision-making unit (DMU) represents one production batch (or observation period) of the biodiesel production process. A total of 18 DMUs were established based on 18 independent production batches collected during the study period. Each DMU was evaluated using the same set of input and output variables to assess its relative eco-efficiency. The input variables included material consumption, electricity, and chemical use, while outputs comprised biodiesel yield and environmental impact scores derived from the LCIA results. The Charnes, Cooper, and Rhodes (CCR) model with constant returns to scale (CRS) was selected, as it is suitable for analyzing proportional relationships between inputs and outputs within the observed production system.

An input-oriented CCR model was adopted because the primary objective of this study is to evaluate the potential reduction in resource consumption and environmental impacts while maintaining the existing biodiesel production level. Since production output is generally determined by market demand and operational requirements, improving sustainability is more realistically achieved by minimizing controllable inputs, including energy consumption, methanol usage, KOH consumption, production costs, and environmental impacts. Therefore, an input-oriented DEA model is considered more appropriate for assessing the eco-efficiency of biodiesel production.

2.5 Eco-technology scenario assessment

To evaluate the potential contribution of eco-technology to improving biodiesel production sustainability, a scenario-based assessment was conducted. Two scenarios were considered: (1) the baseline production system representing the existing operating conditions observed at the biodiesel facility, and (2) an ultrasonic reactor scenario developed based on performance improvements reported in previous studies. The ultrasonic reactor was assumed to reduce energy consumption, methanol usage, and catalyst requirements while maintaining the same biodiesel production output. The modified inventory was subsequently evaluated using the same LCA and DEA framework to estimate its potential environmental and operational performance.

3. RESULTS AND DISCUSSION

3.1 Life cycle analysis

3.1.1 Goal and scope

The first step in conducting a LCA is determining the objectives and scope of the study, a practice foundational to ensuring completeness and accuracy, as reinforced in recent LCA guidelines for biofuel systems [30]. Therefore, the objectives and scope must be clearly defined: in this study, the objective is to identify the potential environmental impacts of the biodiesel production process using UCO from raw material arrival to final biodiesel distribution a cradle-to-customer approach similarly applied in UCO-based LCA research. This study aims to determine each process stage's contribution to total environmental impact, with the scope focusing on energy use, raw materials, and emissions at each process stage, consistent with comprehensive impact assessments in contemporary LCA studies of waste feedstock biodiesel. The analysis includes cradle-to-customer stages raw material collection and transport of UCO, filtration, heating, mixing, settling, methanol removal, dry washing, and final delivery using a functional unit of 950 liters of biodiesel, a standard for process comparability in biodiesel LCA. The level of detail quantifying energy consumption, chemical usage (methanol and catalyst), transport distance, and waste/emissions is supported by the integration of field-collected primary data and secondary sources such as the Ecoinvent database to fill data gaps, in keeping with best practices in recent renewable fuel LCA methodologies [30].

3.1.2 Inventory analysis

Inventory analysis is conducted based on material inputs and outputs within the system. Input data consists of raw material requirements, energy/electricity, water, and transportation equipment used a structure consistent with recent cradle-to-customer LCI studies in biodiesel systems. Inventory of biodiesel production from UCO is conducted based on these inputs and outputs within the system using a cradle-to-customer approach and a functional unit of 950 liters of biodiesel produced and ready for shipment. Input data includes UCO, chemicals (methanol and catalyst), electricity and/or fuel for heating and equipment operation, and transportation during the collection and distribution stages such input categories mirror those detailed in systematic LCA inventories [31].

Inventory output data include the main biodiesel product and by-products such as crude glycerol—whose generation rate and composition (typically ~10% w/w and containing residual methanol, catalyst salts, and organic impurities) are well documented and require downstream purification or valorization strategies [32]. Solid residues from filtration and liquid wastes from washing/cleaning (including spent catalyst solutions) are common process wastes in UCO transesterification and have been quantified and discussed in recent LCA and process-optimization studies as important waste streams that affect overall environmental performance [30]. Air emissions from fuel combustion for transport and heating—primarily CO_2, with notable contributions to NO_x and SO_2 depending on fuel type and combustion conditions—are repeatedly identified in biodiesel LCA literature as key impact drivers and should be included in the inventory with appropriate emission factors [33]. Table 1 therefore presents the complete inventory for producing of biodiesel from UCO, compiling these product, by-product, waste, and emission flows used as input for the LCIA.

To improve the traceability of material flows and ensure consistency with the defined functional unit, a mass balance was established for the biodiesel production process. It is displayed in Table 2. The balance summarizes the conversion of feedstock into biodiesel and by-products while accounting for process losses and auxiliary materials. This presentation facilitates the interpretation of the inventory data and demonstrates the consistency of material flows throughout the system boundary.

3.1.3 Impact assessment

In this study, the impact assessment was conducted using the EDIP 2003 method. The Life Cycle Impact Assessment (LCIA) stage aims to assess the potential environmental impacts arising from resource use and emissions identified in the LCI stage [34]. This process includes an evaluation of ecological impacts, impacts on human health, and the implications of natural resource utilization, with recent methodological advances (e.g., updated toxicity characterization and inclusion of near-field/far-field exposure pathways) improving how human toxicity and ecotoxicity are quantified in LCIA [35] and with dynamic/temporal aspects of LCI–LCIA increasingly recognized for capturing variability in key drivers such as electricity mixes and emissions over time [36]. The LCI therefore serves as the necessary basis for linking a product or process to its potential environmental impacts, while LCIA method choice, characterization factors, and treatment of uncertainty critically determine how those inventory flows are converted into meaningful impact results (recommendations and updated CFs / normalization guidance discussed in recent LCIA technical reviews). LCIA generates a network to represent the flow of processes, materials, and energy throughout a product's life cycle, a visualization style commonly used in recent LCA studies for spotting hotspots and dominant subprocesses [37].

Table 1. Life cycle inventory of used cooking oil (UCO)-based biodiesel production

Process Stage	Input		Output	
	Material	Unit	Material	Unit
Arrival of Raw Materials	Used Cooking Oil	2,198 Kg	Carbon Monoxide	12.606 Kg
			Hydrocarbons	1.39 Kg
			Nitrogen oxides	0.794 Kg
	Truck Transport	270.562 tkm	Particulates	0.01 Kg
			Carbon dioxide	1306.666 Kg
			Sulfur dioxide	0.051 Kg
Filtration	Used Cooking Oil	880 Kg	Waste water	1 liter
			Waste solid	2 Kg
Reactor	Used Cooking Oil	877.36 Kg	Carbon dioxide	1.68 Kg
	Electricity	2.12 kWh		
Mixing	Used Cooking Oil	877 Kg	Carbon dioxide	1.12 Kg
	Methanol	176 Kg		
	KOH	26.4 Kg		
	Electricity	1.14 kWh		
Settling tank	Used Cooking Oil	1079.76 Kg	Carbon dioxide	0.56 Kg
	Electricity	0.71 kWh	Glycerol	216.48 Kg
Methanol removal	Used Cooking Oil	864.16 Kg	Carbon dioxide	2.80 Kg
	Electricity	4 kWh	Residual Methanol	4.4 Kg
Dry Washing	Used Cooking Oil	859.76 Kg	Carbon dioxide	2.24 Kg
	Resin	200 Kg	Residual Glycerol + KOH	23.76 Kg
	Electricity	3 kWh		
Biodiesel Delivery	Biodiesel	880 Kg	Carbon Monoxide	6.13 Kg
			Hydrocarbons	0.674 Kg
			Nitrogen oxides	0.385 Kg
	Truck Transport	68.25 tkm	Particulates	0.004 Kg
			Carbon dioxide	612.717 Kg
			Sulfur dioxide	0.023 Kg

Note: KOH = Potassium Hydroxide.

Table 2. Mass balance of used cooking oil (UCO) biodiesel production

Stream	Mass (kg)	Description
Used cooking oil input	2,198.00	Feedstock collected from all collection areas
Methanol input	176.00	Transesterification reagent
KOH catalyst	26.40	Catalyst
Resin	200.00	Dry washing
Biodiesel product	880.00	Equivalent to approximately 950 L
Glycerol	216.48	By-product
Residual methanol	4.40	Recovery loss
Solid waste	2.00	Filtration residue
Wastewater	1 L	Washing process

Note: KOH = Potassium Hydroxide.

3.1.4 Normalization

The normalization stage helps place LCA results into a clear context, specifically showing how significant the impact is relative to total annual emissions or environmental burdens typical for a region or population. Normalization, which converts the characterization results into Person Equivalent (PE) or milli-PE (mPE) units using the EDIP 2003 normalization factor. Figure 3 displays the normalized results for the entire biodiesel production process, illustrating how normalization can highlight critical environmental hotspots like transportation; similar findings were reported in LCA of regional biofuel supply chains where transport contributed disproportionately to global warming impacts [38]. In addition, Foteinis et al. [12] asserted that the transportation of raw materials significantly influences LCA results in UCO-based biodiesel production. These results demonstrate that the largest impact originates from transporting raw materials from the Kuta area—an observation aligned with studies showing that in biodiesel production, the transport stage often dominates the global warming potential when distribution distances are substantial [34].

3.1.5 Single score

The following Table 3 displays the environmental impact analysis results of UCO biodiesel production, where all impact categories are converted into single-point units (mPt) to summarize the total environmental burden. It is similar to practices employed in recent LCA studies emphasizing endpoint aggregation for easier interpretation [30]. The single score generated from the LCIA analysis was then used as input for the DEA to evaluate the efficiency of the production system [39-41]. The results of the LCA show that UCO-based biodiesel provides superior environmental performance compared to first and third biofuel generation [12].

3.2 Data envelopment analysis results

The first step in DEA is to determine the inputs and outputs for each DMU. Therefore, the specification of inputs and outputs must be clearly defined. This study aims to measure the efficiency of resource utilization in the conversion of UCO into biodiesel, identify inefficiencies, and provide improvement recommendations to optimize the production process. Furthermore, the study compares the efficiency level of biodiesel production with a scenario in which the technology can achieve higher efficiency.

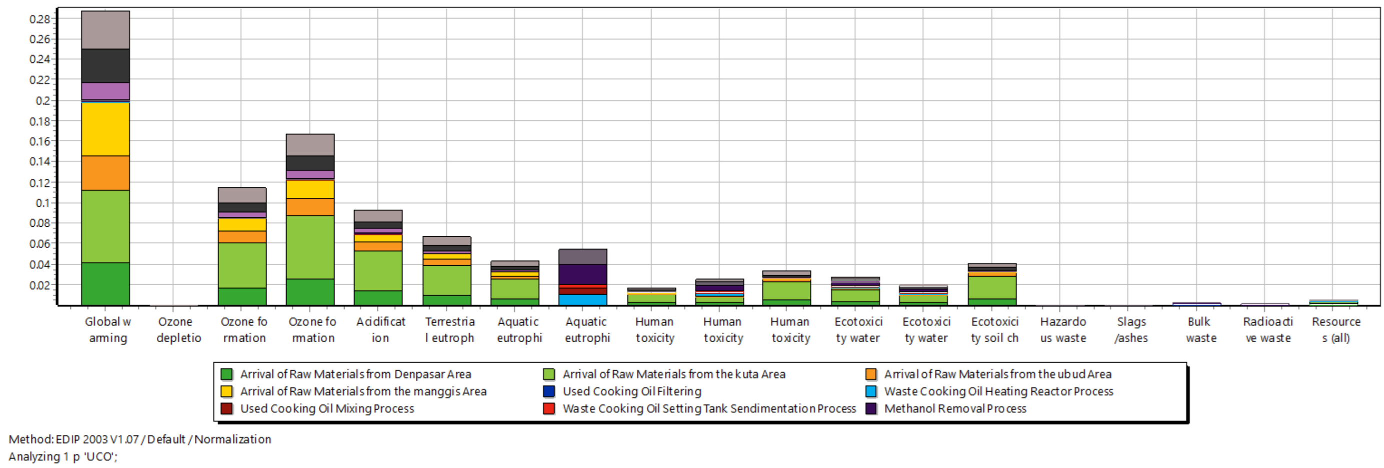

Figure 3. Normalization life cycle assessment (LCA) of used cooking oil (UCO)-based biodiesel production

Table 3. Environmental impact value of used cooking oil (UCO)-based biodiesel production

Process	Environmental Impact Value (mPt)	Process	Environmental Impact Value (mPt)
Arrival of Raw Materials from Denpasar Area	0.144	Used Cooking Oil Settling Tank Sedimentation Process	0.006
Arrival of Raw Materials from the Kuta Area	0.353	Methanol Removal Process	0.033
Arrival of Raw Materials from the Ubud Area	0.101	Dry Washing Process of Used Cooking Oil	0.024
Arrival of Raw Materials from the Mangosteen Area	0.116	Biodiesel Delivery to Denpasar Area	0.068
Used Cooking Oil Filtering	0.00163	Biodiesel Delivery to Kuta Area	0.112
Used Cooking Oil Heating Reactor Process	0.017	Biodiesel Delivery in Ubud Area	0.169
Used Cooking Oil Mixing Process	0.009		
	Total		1.15

Table 4. Proposed objective, input, output and decision-making unit (DMU) of used cooking oil (UCO)-based biodiesel production

Criteria	Type of Data
Objective	To optimize the efficiency of the used cooking oil processing into biodiesel
Inputs	Environmental impact value The price of used cooking oil The price of methanol The price of KOH The consumption of methanol The consumption of KOH Energy
Outputs	The volume of biodiesel
Decision-Making Units (DMUs)	DMU 1 - DMU 18

Note: KOH = Potassium Hydroxide.

Based on Table 4, the study employs seven input and one output variables. The environmental impact, which was previously considered an output in the LCA analysis, is treated as one of the inputs in the DEA, reflecting the growing use of combined LCA- DEA frameworks to capture both environmental burdens and production efficiency in a single evaluation system [39]. Other input variables include the price of UCO, the price of methanol, the price of KOH, the consumption of methanol, the consumption of KOH, and energy. Meanwhile, the volume of biodiesel produced is defined as the output. This study covers 18 DMUs, representing 18 different data collection periods.

Subsequently, the study will evaluate and rank the efficiency of processing UCO into biodiesel, as illustrated in Figure 4. The results of the efficiency score analysis showed a variation in relative performance between DMUs in utilizing resources to produce biodiesel output. A total of three DMUs (DMU15, DMU16, and DMU18) managed to achieve a score of 100%, which puts them in the frontier efficient category. These units can be considered as benchmarks and peer references because they are able to operate at the frontier of efficiency. Most DMUs achieved efficiency scores ranging from 91% to 99%, indicating that they operated close to the efficient frontier but had not yet reached full efficiency. Only three DMUs (DMU15, DMU16, and DMU18) achieved an efficiency score of 1.00 and were therefore classified as frontier-efficient under the CCR DEA model. This shows that although it has not fully reached the frontier, the majority of DMUs have been operating quite close to optimal conditions. However, there are 3 DMUs that are still in the moderate category, such as DMU4 (94%), DMU6 (87%), and DMU12 (92%). This indicates that there is a significant potential for a significant reduction in inputs, especially in energy and chemicals. This score distribution confirms that the relative efficiency between DMUs is not uniform, but is generally dominated by units that are close to the frontier. Thus, DMUs that are classified as moderate need to be directed to imitate the input usage pattern of frontier efficient DMUs. Through this benchmarking approach, it is hoped that an increase in collective performance can be achieved as well as a reduction in costs and environmental impact of the entire biodiesel production system.

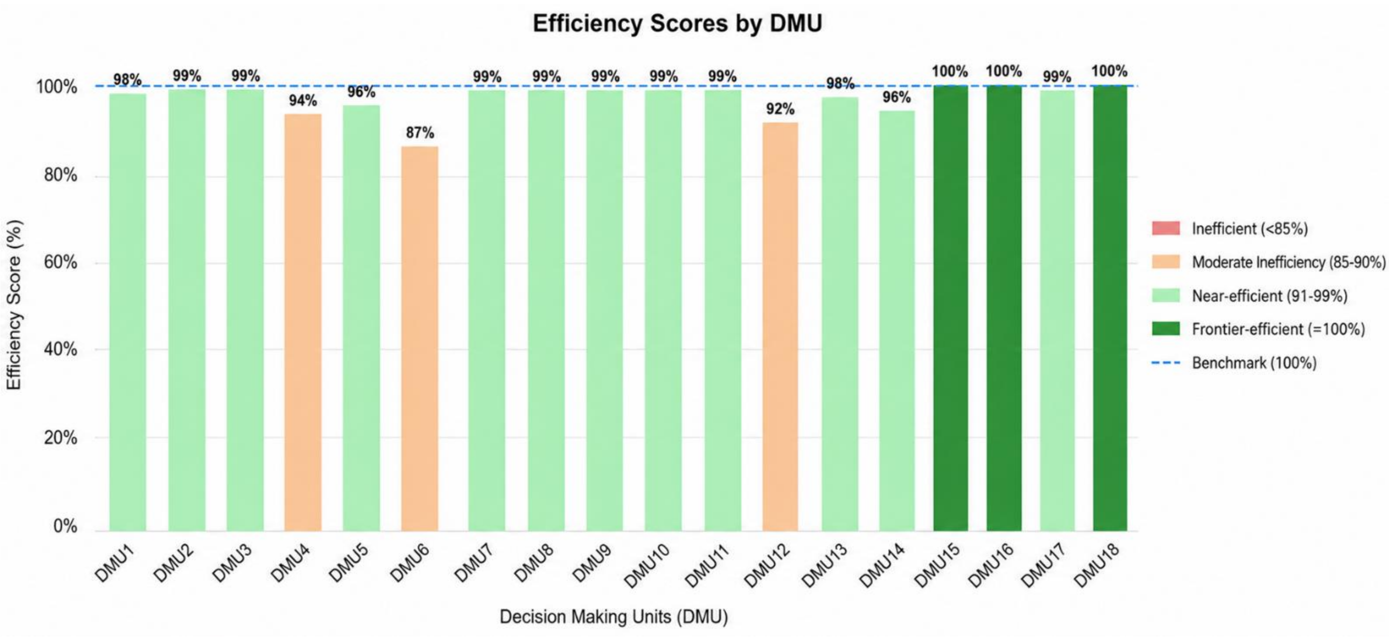

Figure 4. Efficiency scores of the used cooking oil (UCO) to biodiesel production process

In Table 5, the results of the classification of the causes of inefficiency show that the majority of DMUs face problems with the excessive use of methanol, energy, and catalysts. In detail, as many as 5 DMUs (27.8%) experienced inefficiency due to excessive methanol consumption, such as DMU1–DMU4, and DMU12. Meanwhile, 8 DMUs (44.4%) faced problems with excessive energy use, as seen in DMU5, DMU6, DMU7–DMU9, DMU11–DMU14. In addition, 10 DMUs (55.6%) were shown to have excess use of KOH catalysts, which were spread across almost all inefficient units, including DMU1–DMU4, DMU6–DMU14, and DMU17. The DMU15, DMU16, and DMU18, which each achieved a score of 100%, did not show any cause of inefficiency, so it could be used as a benchmark. This finding confirms that the dominant factor causing inefficiency is excessive consumption of catalysts, followed by energy use, and then methanol. Therefore, improvements need to be made to achieve maximum company efficiency, one of which is by simulating improvements in the factors that cause inefficiency in each DMU.

Table 5. Classification of causes of decision-making unit (DMU) inefficiency

DMU	Efficiency	Classification	Causes of Inefficiency
DMU 1	98%	Efficient	Methanol and KOH too high
DMU 2	99%	Efficient	Methanol and KOH too high
DMU 3	99%	Efficient	Methanol and KOH too high
DMU 4	94%	Moderate	Methanol and KOH too high
DMU 5	96%	Efficient	Energy and KOH too high
DMU 6	87%	Moderate	Energy and KOH too high
DMU 7	99%	Efficient	Energy and KOH too high
DMU 8	99%	Efficient	Energy and KOH too high
DMU 9	99%	Efficient	Energy and KOH too high
DMU 10	99%	Efficient	KOH too high
DMU 11	99%	Efficient	Energy and KOH too high
DMU 12	92%	Moderate	Energy, Methanol, and KOH too high
DMU 13	98%	Efficient	Energy and KOH too high
DMU 14	96%	Efficient	Energy and KOH too high
DMU 15	100%	Frontier efficient	-
DMU 16	100%	Frontier efficient	-
DMU 17	99%	Efficient	KOH too high
DMU 18	100%	Frontier efficient	-

Note: KOH = Potassium Hydroxide.

4. CONCLUSIONS

This study evaluated the sustainability performance of UCO-based biodiesel production in Indonesia, using an integrated framework of LCA and DEA. The synergy of eco-efficiency principles and the adoption of ultrasonic reactor technology as an eco-technology represented a highly effective and feasible strategy to enhance the sustainability of UCO-based biodiesel production. The results showed a total environmental impact of 1.15 mPt, with the largest contributions coming from the collection of UCO (0.353 mPt) and biodiesel distribution (0.169 mPt), mainly dominated by global warming, aquatic eutrophication, and acute water toxicity. In terms of conventional efficiency, only three out of 18 DMUs (16.67%) were deemed efficient, with the main sources of inefficiency being the excessive use of KOH catalyst (55.6%), energy (44.4%), and methanol (27.8%). Despite providing valuable insights, the study has several limitations, such as its focus on operational field conditions that restrict the exploration of innovative solutions, the cradle-to-customer boundary in the LCA, limited generalizability due to a single case study, and inconsistencies in efficiency data. The managerial implications suggest that the production facility should consider adopting ultrasonic reactor technology to achieve higher production efficiency and cost savings, optimize supply chain and logistics to minimize environmental impacts, conduct internal benchmarking with efficient DMUs to address excessive raw material usage, utilize the LCA- DEA framework for data-driven sustainable decision-making, and explore diversification of UCO-derived products to strengthen the company's economic resilience.

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DATA AVAILABILITY STATEMENT

Raw data were generated at Lengis Hijau (LH) facilities, and the data supporting this study's findings are available from the corresponding author, F.A., on reasonable request.

COMPETING INTERESTS

The authors declare they have no conflicts of interest related to this article.

REFERENCES

[1] Sovacool, B.K. (2013). An international assessment of energy security performance. Ecological Economics, 88: 148-158. https://doi.org/10.1016/j.ecolecon.2013.01.019

[2] Kumar, D., Singh, B. (2019). Role of biomass supply chain management in sustainable bioenergy production. Biofuels, 10(1): 109-119. https://doi.org/10.1080/17597269.2017.1368060

[3] Setiawan, V.N. (2025). Mau kejar biodiesel B50 di 2026, pemerintah masih terkendala isu ini. CNBC Indonesia. https://www.cnbcindonesia.com/news/20250314161317-4-618750/mau-kejar-biodiesel-b50-di-2026-pemerintah-masih-terkendala-isu-ini.

[4] Biru, M.D. (2024). Energi terbarukan: Analisis kebijakan pemanfaatan biodisel kelapa sawit sebagai bahan bakar nabati nasional di tengah kontroversinya sebagai faktor pendorong deforestasi. Trendand Future of Agribusiness, 1(1): 1-11. https://doi.org/10.61511/tafoa.v1i1.2024.543

[5] Van Grinsven, A., van den Toorn, E., van der Veen, R., Kampman, B. (2020). Used Cooking Oil (UCO) as biofuel feedstock in the EU. CE Delft: Delft, The Netherlands, 200247.

[6] Kristiana, T., O'Connell, A., Baldino, C. (2023). Producing high quality biodiesel from used cooking oil in Indonesia. The International Council on Clean Transportation. https://theicct.org/publication/producing-high-quality-biodiesel-from-used-cooking-oil-in-indonesia-aug23/.

[7] Manikandan, G., Kanna, P.R., Taler, D., Sobota, T. (2023). Review of waste cooking oil (WCO) as a feedstock for biofuel—Indian perspective. Energies, 16(4): 1739. https://doi.org/10.3390/en16041739

[8] Kristiana, T., Baldino, C., Searle, S. (2022). An estimate of current collection and potential collection of used cooking oil from major Asian exporting countries. The International Council on Clean Transportation, 1-21. https://theicct.org/wp-content/uploads/2022/02/UCO-from-Asia_wp_final.pdf.

[9] Suryatini, K.Y., Made, M.N. (2023). Pemanfaatan potensi minyak goreng bekas (jelantah) sebagai biodiesel. Emasains: Jurnal Edukasi Matematika dan Sains, 12(1): 116-124. https://doi.org/10.5281/zenodo.7902815

[10] Kharina, A., Searle, S., Rachmadini, D., Kurniawan, A.A., Prionggo, A. (2018). The potential economic, health and greenhouse gas benefits of incorporating used cooking oil into Indonesia's biodiesel. White Paper. https://theicct.org/sites/default/files/publications/UCO_Biodiesel_Indonesia_20180919.pdf.

[11] 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): 3248. https://doi.org/10.3390/en13123248

[12] Foteinis, S., Chatzisymeon, E., Litinas, A., Tsoutsos, T. (2020). Used-cooking-oil biodiesel: Life cycle assessment and comparison with first- and third-generation biofuel. Renewable Energy, 153: 588-600. https://doi.org/10.1016/j.renene.2020.02.022

[13] Patel, K., Singh, S.K. (2024). Sustainable biodiesel from used cooking oil: A comparative life cycle, energy, and uncertainty analysis. Environment, Development and Sustainability, 27: 14755-14780. https://doi.org/10.1007/s10668-024-05692-1

[14] Hartini, S., Puspitasari, D., Aisy, N.R., Widharto, Y. (2020). Eco-efficiency level of production process of waste cooking oil to be biodiesel with life cycle assessment. E3S Web of Conferences, 202: 10004. https://doi.org/10.1051/e3sconf/202020210004

[15] Corral-Bobadilla, M., Lostado-Lorza, R., Somovilla-Gómez, F., Íñiguez-Macedo, S. (2022). Life cycle assessment multi-objective optimization for eco-efficient biodiesel production using waste cooking oil. Journal of Cleaner Production, 359: 132113. https://doi.org/10.1016/j.jclepro.2022.132113

[16] Mgoma, S.T., Basitere, M., Mshayisa, V.V., De Jager, D. (2025). A systematic review on sustainable extraction, preservation, and enhancement in food processing: The advancement from conventional to green technology through ultrasound. Processes, 13(4): 965. https://doi.org/10.3390/pr13040965

[17] Zhang, Y., Mao, Y.Y., Jiao, L.D., Shuai, C.Y., Zhang, H.S. (2021). Eco-efficiency, eco-technology innovation and eco-well-being performance to improve global sustainable development. Environmental Impact Assessment Review, 89: 106580. https://doi.org/10.1016/j.eiar.2021.106580

[18] Brodjonegoro, S.S. (2012). Eco-technology and the prospect of Indonesia. Journal of Ecotechnology Research, 16(3-4): 75-78. https://doi.org/10.11190/jer.16.75

[19] Müller, M.O., Kaufmann-Hayoz, R., Schwaninger, M., Ulli-Beer, S. (2013). The diffusion of eco-technologies: A model-based theory. In Energy Policy Modeling in the 21st Century. Understanding Complex Systems, Springer, New York, pp. 49-67. https://doi.org/10.1007/978-1-4614-8606-0_4

[20] Kataki, S., Chatterjee, S., Vairale, M.G., Dwivedi, S.K., Gupta, D.K. (2021). Constructed wetland, an eco-technology for wastewater treatment: A review on types of wastewater treated and components of the technology (macrophyte, biolfilm and substrate). Journal of Environmental Management, 283: 111986. https://doi.org/10.1016/j.jenvman.2021.111986

[21] Yıldız-Ozturk, E., Askin-Uzel, R. (2023). Advanced bioengineering applications with eco-technology approach for sustainable development. In Circular Business Management in Sustainability. ISCMEE 2022. Lecture Notes in Management and Industrial Engineering, pp. 182-208. https://doi.org/10.1007/978-3-031-23463-7_12

[22] Taoda, H. (2009). Development and applications of photocatalytic technology — Industrialization of sustainable eco-technology. Synthesiology English Edition, 1(4): 263-272. https://doi.org/10.5571/syntheng.1.263

[23] Chauhan, J.S., Kumar, S. (2020). Wastewater ferti-irrigation: An eco-technology for sustainable agriculture. Sustainable Water Resources Management, 6: 31. https://doi.org/10.1007/s40899-020-00389-5

[24] Jeyaseelan, T., El Samad, T., Rajkumar, S., Chatterjee, A., Al-Zaili, J. (2023). A techno-economic assessment of waste oil biodiesel blends for automotive applications in urban areas: Case of India. Energy, 271: 127021. https://doi.org/10.1016/j.energy.2023.127021

[25] Permpool, N., Mahmood, A., Ghani, H.U., Gheewala, S.H. (2021). An eco-efficiency assessment of bio-based diesel substitutes: A case study in Thailand. Sustainability, 13(2): 576. https://doi.org/10.3390/su13020576

[26] Sueyoshi, T. (2017). Damages to return with a possible occurrence of eco-technology innovation measured by DEA environmental assessment. Journal of Economic Structures, 6: 7. https://doi.org/10.1186/s40008-017-0067-x

[27] Nascimento, L., Ribeiro, A., Ferreira, A., et al. (2021). Turning waste cooking oils into biofuels—Valorization technologies: A review. Energies, 15(1): 116. https://doi.org/10.3390/en15010116

[28] Zhao, E., Walker, P.D., Surawski, N.C., Bennett, N.S. (2021). Assessing the life cycle cumulative energy demand and greenhouse gas emissions of lithium-ion batteries. Journal of Energy Storage, 43: 103193. https://doi.org/10.1016/j.est.2021.103193

[29] Gold, S., Reiner, G., Dion, P. (2017). Data envelopment analysis for investigating the relative efficiency of supply chain management. Logistics Research, 10(6): 1-17. https://doi.org/10.23773/2017_6

[30] Musharavati, F., Sajid, K., Anwer, I., et al. (2023). Advancing biodiesel production system from mixed vegetable oil waste: A life cycle assessment of environmental and economic outcomes. Sustainability, 15(24): 16550. https://doi.org/10.3390/su152416550

[31] Kumar, A., Bhayana, S., Singh, P.K., et al. (2025). Valorization of used cooking oil: Challenges, current developments, life cycle assessment and future prospects. Discover Sustainability, 6: 119. https://doi.org/10.1007/s43621-025-00905-7

[32] Oliveira, M., Ramos, A., Monteiro, E., Rouboa, A. (2022). Improvement of the crude glycerol purification process derived from biodiesel production waste sources through computational modeling. Sustainability, 14(3): 1747. https://doi.org/10.3390/su14031747

[33] Aljaafari, A., Fattah, I.M.R., Jahirul, M.I., et al. (2022). Biodiesel emissions: A state-of-the-art review on health and environmental impacts. Energies, 15(18): 6854. https://doi.org/10.3390/en15186854

[34] Barahmand, Z., Eikeland, M.S. (2022). Life cycle assessment under uncertainty: A scoping review. World, 3(3): 692-717. https://doi.org/10.3390/world3030039

[35] Fantke, P., Chiu, W.A., Aylward, L., et al. (2021). Exposure and toxicity characterization of chemical emissions and chemicals in products: Global recommendations and implementation in USEtox. International Journal of Life Cycle Assessment, 26: 899-915. https://doi.org/10.1007/s11367-021-01889-y

[36] Cornago, S., Tan, Y.S., Brondi, C., Ramakrishna, S., Low, J.S.C. (2022). Systematic literature review on dynamic life cycle inventory: Towards industry 4.0 applications. Sustainability, 14(11): 6464. https://doi.org/10.3390/su14116464

[37] Bajdur, W.M., Włodarczyk-Makuła, M., Krukowska-Miler, A. (2024). Application of the life cycle assessment (LCA) method in assessing the environmental impact of new materials derived from waste polymers in terms of sustainability. Sustainability, 16(22): 9759. https://doi.org/10.3390/su16229759

[38] Vunnava, V.S.G., Singh, S. (2020). Spatial life cycle analysis of soybean-based biodiesel production in Indiana, USA using process modeling. Processes, 8(4): 392. https://doi.org/10.3390/pr8040392

[39] Mohammadi, A., Venkatesh, G., Eskandari, S., Rafiee, S. (2022). Eco-efficiency analysis to improve environmental performance of wheat production. Agriculture, 12(7): 1031. https://doi.org/10.3390/agriculture12071031

[40] Kock, B., Friedl, A., Loaiza, S.S., Wukovits, W., Mihayi-

Schneider, B. (2023). Automation of life cycle assessment—A critical review of developments in the field of life cycle inventory analysis. Sustainability, 15(6): 5531. https://doi.org/10.3390/su15065531

[41] Linares, R., Lopez-Uceda, A., Piccinali, A., Martinez-Ruedas, C., Galvin, A.P. (2024). LCA applied to comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources. Environmental Science and Pollution Research, 31: 44023-44035. https://doi.org/10.1007/s11356-024-33868-9