Journal of Business, Social and Technology
Volume 7, Issue 3, 912-928
e_ISSN: 2807-6362
https://bustechno.polteksci.ac.id/index.php/jbt/index
DOI: doi.org/10.59261/jbt.v7i3.688

Life Cycle Environmental Performance of B100 Biodiesel from Reutealis Trisperma (Kemiri Sunan): An Integrated Carbon Payback Period and Nature-Based Solutions Assessment

***Kiki Hakiki**
Universitas Airlangga, Indonesia

Dedi Priadi
Universitas Airlangga, Indonesia

***Corresponding author:**
Kiki Hakiki, Universitas Indonesia, Indonesia.
✉hafisah@gmail.com

Article Info:
***Article history*:**
Received: May 31, 2026
Revised: July 06, 2026
Accepted: July 13, 2026

***Keywords*:**
B100 Biodiesel; Carbon Payback Period; Kemiri Sunan; Life Cycle Assessment; Reutealis Trisperma

Abstract

Background: Rising greenhouse gas emissions have increased the need for sustainable biofuels. Biodiesel from the non-edible feedstock Reutealis trisperma (kemiri sunan) offers a low-carbon alternative compatible with marginal lands under the Nature-Based Solutions (NbS) framework.
Objective: This study evaluates the environmental performance of B100 biodiesel production from *kemiri sunan* and quantifies the effects of renewable energy integration on emission reduction, energy efficiency, and carbon payback.
Methods: A Life Cycle Assessment (LCA) using a cradle-to-gate system boundary (functional unit: 1 liter of B100 biodiesel) was conducted using OpenLCA with the Ecoinvent 3.11 database, ReCiPe 2016 Midpoint (H), IPCC 2013, and Cumulative Energy Demand methods. The assessment covered the entire production chain from cultivation to bio-additive blending.
Results: The carbon emissions of *kemiri sunan* B100 biodiesel were 2.04 kg CO_2-eq per liter, which were significantly lower than those of fossil diesel (3,400 kg CO_2-eq/ton) and comparable to palm oil biodiesel (1,659 kg CO_2-eq/ton). Transitioning to solar photovoltaic (PV) electricity reduced emissions by 56% (from 2.02 to 0.74 kg CO_2-eq). Energy balance indicators, including Net Energy Gain (NEG), Net Energy Ratio (NER), and Specific Energy Consumption (SEC), confirmed a positive energy output-to-input ratio. The Carbon Payback Period (CPP) was estimated at 11 years when using PLN electricity and was shortened to 6 years with solar PV integration.
Conclusion: *Kemiri sunan* B100 biodiesel demonstrates strong potential as a sustainable, non-edible bioenergy source that supports low-carbon energy transitions. The integration of renewable energy, optimized cultivation management, and the utilization of degraded lands collectively enhance its environmental performance and strengthen the effectiveness of NbS implementation.

To cite this article: Hakiki, K., & Priadi, D. (2026). Life cycle environmental performance of B100 biodiesel from Reutealis trisperma (kemiri sunan): An integrated carbon payback period and nature-based solutions assessment. *Journal of Business, Social and Technology, 7*(3), 912–928. https://doi.org/10.59261/jbt.v7i3.688

INTRODUCTION

Global natural disasters, including floods and landslides, are increasing in frequency, while climate change disrupts agricultural patterns (Azadi et al., 2022). For instance, declining global coffee supply has driven green bean robusta prices from IDR 40,000 to IDR 80,000 per kg. Sustainability, defined as meeting present needs without compromising the ability of future generations to meet their own needs Hajian (2021), has therefore become a central global concern encompassing economic, social, and environmental dimensions.

The global average surface temperature in 2024 reached 1.28 °C above the 1951–1980 baseline and 1.47 °C above pre-industrial levels (1850–1900), making the last decade the warmest on record (Global Temperature - Earth Indicator - NASA Science 2021). This warming trajectory has intensified collective efforts to reduce greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), across all economic sectors.

The global average surface temperature in 2024 was recorded at 2.3 °F, approximately 1.28 °C higher than the 20th-century average temperature for the reference period of 1951–1980. According to NASA records, this global temperature was also 2.65 °F (1.47 °C) warmer than the pre-industrial average temperature during the late 19th century (1850–1900). The last ten years have been identified as the warmest period in the history of global temperature records (Global Temperature - Earth Indicator - NASA Science 2021).

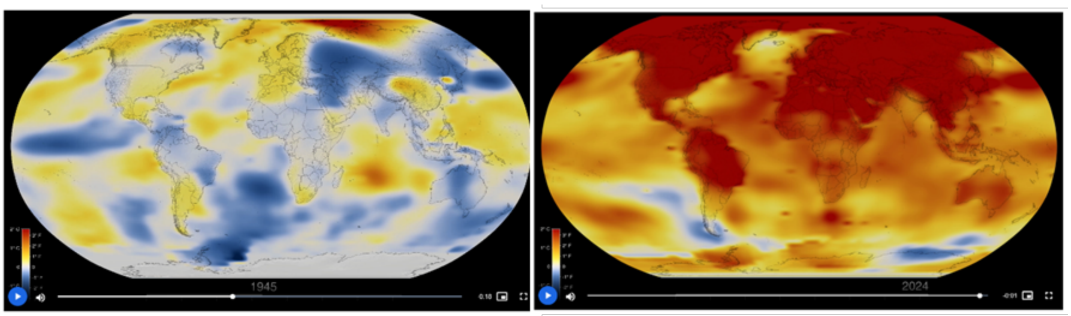

Figure 1. Visualization of Temperature Color Differences

The main sources of global carbon emissions include the transportation, industrial, electricity generation, and construction sectors, with energy consumption being the largest contributor to greenhouse gas (GHG) emissions resulting from human activities, accounting for more than 70% of total emissions (Kao & Chen, 2025). In the transportation sector, land transport contributes approximately three-quarters of the total carbon emissions within this sector. The contribution of transportation to carbon emissions primarily originates from the consumption of fossil fuels, such as gasoline and diesel, in motor vehicles. The increasing number of private vehicles, urban population growth, and expansion of logistics and freight distribution networks have accelerated energy consumption in this sector.

According to the Renewable Energy Policy Network for the 21st Century (REN21) 2025 report, between 2022 and 2023, total final energy consumption (TFEC) in the transport sector increased by 3.6%, surpassing pre-COVID-19 levels for the first time by 0.8%. Although renewable energy use in the transport sector increased by 56% between 2013 and 2023, the sector remains highly dependent on fossil fuels, with renewable energy accounting for only 3.6% of TFEC in 2023. During the same period, transport energy demand increased by 14%, while non-renewable energy consumption increased by 13%. Of the total renewable energy consumed in 2023, transport biofuels accounted for only 1.2% (*GSR 2025*).

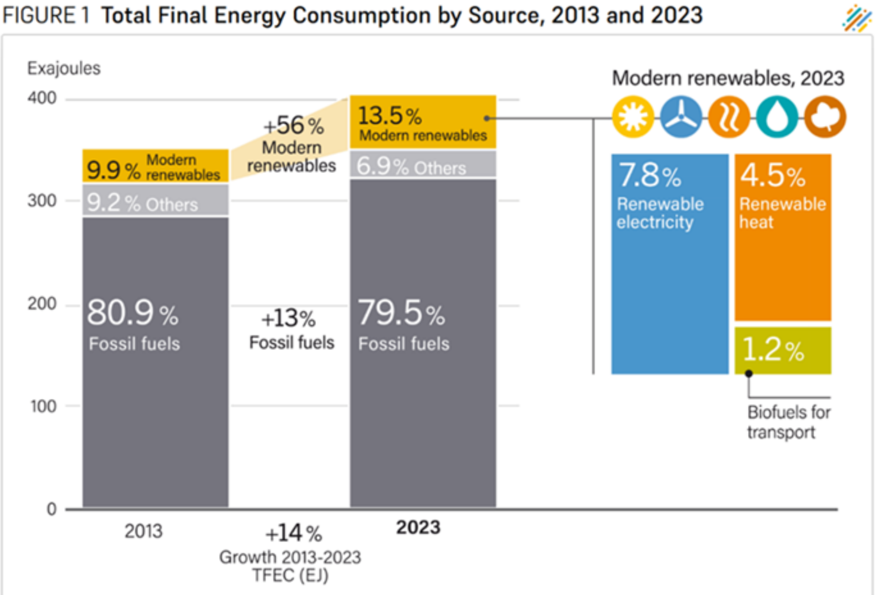

Figure 2. Total Final Energy Consumption by Source, 2013 and 2023

Global demand for biofuels reached 175.2 billion liters in 2023, continuing a steady upward trend over the past decade. Bioethanol remains the most widely used type of biofuel, followed by biodiesel (fatty acid methyl ester [FAME]) and renewable diesel.

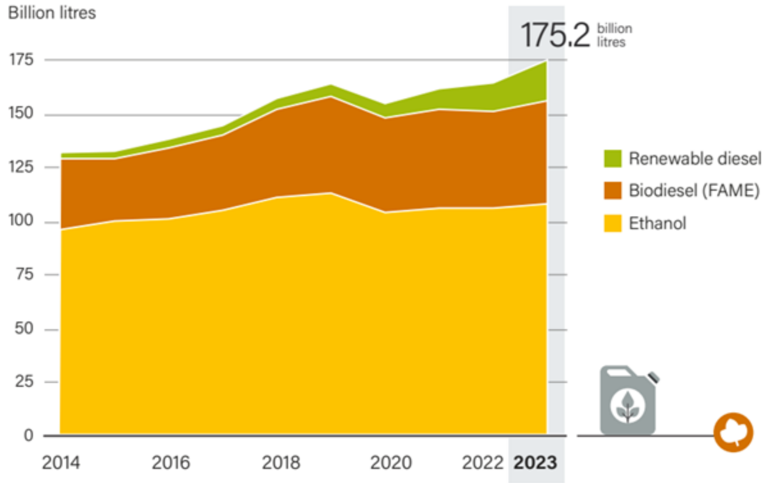

Figure 3. Global Biofuel Demand in 2023

Based on the description above, with the global biofuel share currently at 1.2% and biodiesel demand reaching approximately 50 billion liters, research and development opportunities remain widely open. Indonesia's achievement on the global stage is reflected in its successful development of B35 and B40 biodiesel derived from palm oil. Indonesia's diesel consumption decreased to approximately 40,000 kiloliters in 2024. Nevertheless, biodiesel production from palm oil continues to face several challenges related to competition with edible oil consumption and environmental degradation caused by forest land conversion. These environmental impacts include declining soil fertility and high water consumption, raising concerns regarding the long-term requirement for soil fertility restoration in Indonesia.

Based on a literature review, several studies have explored more environmentally sustainable biodiesel feedstock alternatives in Indonesia. One such study was conducted by the Balai Perakitan dan Pengujian Tanaman Industri dan Penyegar (BRMP TRI), Ministry of Agriculture, located in Parung Kuda, Sukabumi Regency, Indonesia. *Reutealis trisperma* (*kemiri sunan*) is a non-edible feedstock that has become the focus of research and development for conversion into B100 biodiesel. This research provides baseline data on environmental impacts, process conditions, and technical performance evaluations for the development of B100 biodiesel derived from *kemiri sunan*.

At the national level, Indonesia possesses approximately 10 million hectares of marginal and degraded land that are potentially suitable for non-edible energy crop cultivation (Nesshöver et al., 2017). *Kemiri sunan* (*Reutealis trisperma*) has been identified as one of the most promising non-edible biodiesel feedstocks in Indonesia, with an oil content ranging from 52–58% and an estimated biodiesel production potential of 1–3 tons per hectare under optimal agroforestry management conditions (Herman et al., 2023). The current national B35–B40 biodiesel program relies predominantly on palm oil, which raises concerns regarding food–energy competition and land-use change. Therefore, diversifying biodiesel feedstocks toward non-edible sources such as *kemiri sunan* represents a strategic pathway for advancing sustainable bioenergy development in Indonesia.

The novelty of this research lies in the simultaneous integration of a comprehensive Life Cycle Assessment (LCA) using the latest Ecoinvent 3.11 database and updated field data from 2026, energy balance quantification through Net Energy Gain (NEG), Net Energy Ratio (NER), and Specific Energy Consumption (SEC) indicators, and Carbon Payback Period (CPP) analysis that combines biodiesel production emissions with biological carbon sequestration within a Nature-Based Solutions (NbS) framework. This integrated approach extends previous *Reutealis trisperma* (*kemiri sunan*) LCA studies Sucahyo (2025) by incorporating renewable electricity scenario modelling and CPP analysis into a unified assessment framework. These approaches have not previously been applied simultaneously to this feedstock.

Based on this background, this study aims to evaluate the environmental performance of *Reutealis trisperma*-based B100 biodiesel by comparing its Climate Change impacts with those of fossil diesel and palm oil biodiesel. Furthermore, this study assesses the Carbon Payback Period (CPP) of the biodiesel production system integrated with *Zelkova serrata*carbon sequestration under two electricity scenarios, namely the PLN grid electricity scenario and Solar PV electricity scenario. In addition, this study examines the effectiveness of integrating vegetation-based Nature-Based Solutions (NbS) in accelerating the achievement of net-zero emissions. Theoretically, this research contributes to the development of an integrated LCA–CPP–NbS assessment framework applicable to non-edible bioenergy systems. Practically, the findings provide science-based recommendations for the sustainable implementation of *Reutealis trisperma* biodiesel in Indonesia, particularly through the adoption of Solar PV systems and agroforestry management practices on marginal lands.

METHOD

This research was divided into two main stages: the quantification of environmental impacts using the Life Cycle Assessment (LCA) method and the calculation of the carbon payback period. A research flow diagram was used to illustrate the overall research methodology, from data collection to result interpretation. The initial stage of the research involved defining the goal and scope of the LCA analysis using a cradle-to-gate approach to describe the entire B100 biodiesel production cycle. The analyzed system included land preparation, plant cultivation, fruit harvesting, shell and kernel separation, oil extraction, two-stage transesterification, biodiesel washing, and bio-additive addition until biodiesel that met ASTM D6751 standards as a substitute for fossil diesel fuel was obtained.

The functional unit used was 1 liter of B100 biodiesel produced using a machine capacity of 3,000 liters. Environmental impact analysis was performed using OpenLCA software with the Ecoinvent database and the ReCiPe 2016 Midpoint (H) method to evaluate 18 environmental impact categories, while the Cumulative Energy Demand method was used to calculate the energy balance through parameters such as Net Energy Gain (NEG), Net Energy Ratio (NER), and Specific Energy Consumption (SEC).

The cradle-to-gate system boundary was deliberately selected over a cradle-to-grave approach because this study focused on evaluating the environmental performance of the biodiesel production chain itself prior to the use phase. This choice was consistent with standardized practices in bioenergy LCA studies that aim to isolate production-phase hotspots and compare feedstock processing chains under controlled conditions (Sucahyo et al., 2025; Tibesigwa et al., 2023). Including the use phase would have introduced additional variability related to vehicle types, combustion efficiency, and end-of-life scenarios, which were beyond the defined research objectives. A sensitivity analysis boundary note was provided in the limitations section.

The next stage was the Life Cycle Inventory (LCI) analysis, which was conducted by identifying all inputs and outputs of the B100 biodiesel production system. Input data included energy consumption, raw materials, process chemicals, methanol, catalysts, process water, and infrastructure requirements, while outputs included B100 biodiesel, glycerol, air emissions, liquid waste, solid waste, and other process residues. Data were obtained through direct observations and interviews at BRMP TRI as primary data sources, as well as from scientific literature and previous studies as secondary data sources.

Subsequently, impact assessment and interpretation were performed using the ReCiPe 2016 Midpoint (H) and IPCC 2013 methods to identify emission hotspots and compare the production process with previous research findings. Furthermore, this study integrated a Nature-Based Solutions (NbS) approach through Carbon Payback Period (CPP) analysis by comparing emissions from the PLN and Solar PV electricity scenarios with the carbon sequestration capacity of Zelkova serrata. The CPP calculation was performed by comparing the annual emissions of biodiesel production with the cumulative carbon sequestration of the plant until the carbon break-even point was reached, thereby determining the effectiveness of integrating renewable energy and carbon-sequestering vegetation in supporting a sustainable low-carbon energy transition.

Although Zelkova serrata is not a species native to Indonesia, its selection as the Carbon Payback Period reference model was scientifically justified based on data availability and methodological transparency. Zelkova serrata has well-documented long-term carbon sequestration growth curves derived from peer-reviewed studies Jo (2017), providing a standardized and reproducible reference for demonstrating the CPP calculation methodology. The authors acknowledged that using a native Indonesian tree species would strengthen ecological representativeness; however, longitudinal carbon accumulation data for tropical species comparable to Zelkova serrata remained scarce in the peer-reviewed literature (Cook-Patton et al., 2020). Future research is recommended to develop CPP models using local carbon-sequestering species such as Shorea spp. or Albizia spp. under Indonesian agroforestry conditions.

The ReCiPe 2016 Midpoint (H) method was selected because it provides comprehensive and harmonized coverage of 18 impact categories and is widely adopted in LCA studies of bioenergy systems (Huijbregts et al., 2017; Sala et al., 2020). The Hierarchist (H) perspective was preferred over the Individualist or Egalitarian perspectives because it balances short- and long-term environmental considerations, making it a relevant framework for sustainability assessments. IPCC 2013 characterization factors were applied specifically to the Climate Change impact category to ensure consistency with international greenhouse gas accounting protocols and enable direct comparison with fossil fuel benchmarks. The Ecoinvent 3.11 database Wernet (2016) was selected because of its high-resolution background system data and updated electricity grid inventories representing Indonesian conditions.

Primary data collection at BRMP TRI was conducted through structured field observations and semi-structured interviews with senior technical staff and research officers between January and March 2026. Observations covered all twelve production stages, from land cultivation to bio-additive blending, with measurements recorded for material quantities, energy consumption (based on kWh meter readings), and process durations. Interview protocols focused on machine capacities, maintenance records, and operational parameters. Data validation was performed through triangulation by cross-referencing direct measurements with maintenance logbooks, production reports, and mass balance calculations. Where primary data were unavailable, secondary data from the Ecoinvent 3.11 database and peer-reviewed literature were used as proxies and were clearly distinguished in the Life Cycle Inventory tables.

RESULTS AND DISCUSSION

Results

Operating Conditions of the Kemiri Sunan B100 Biodiesel Process

The research on the B100 biodiesel manufacturing process using a machine at BRMP TRI was conducted by utilizing hybrid reactor technology, free fatty acid (FFA) reduction, and a two-stage biodiesel processing approach under controlled operating conditions, including reaction temperature, methanol-to-oil molar ratio, catalyst concentration, and reaction time, to achieve optimal conversion. The production process begins with the cultivation and maintenance of *kemiri sunan*, followed by harvesting, transportation of raw materials, and biodiesel processing through oil extraction, FFA reduction, transesterification, purification, and biodiesel quality testing in accordance with applicable standards.

Table 1. Operating Conditions of Kemiri Sunan at BRMP TRI

No	Description	Amount	Unit
1	Land area	4	hectares
2	Fruit production per year	26,751	pieces (pcs)
3	Age of *kemiri sunan* plants	6	years
4	Number of *kemiri sunan* plants	521	trees
5	Processes modeled	12	processes

Comparison of Cultivation and Biodiesel Process between Palm Oil and Kemiri Sunan

The ecological characteristics of oil palm and *kemiri sunan* (*Reutealis trisperma*) show contrasting differences. Oil palm is intensively cultivated at high densities on highly fertile land and is capable of producing approximately 3–4 tons of biodiesel per hectare per year Siregar (2015), but its expansion may also exert significant pressure on soil quality and biodiversity due to large-scale plantation development. Conversely, *kemiri sunan* has a lower planting density, tolerates less fertile land conditions, and can be integrated into intercropping systems as a shade tree for coffee plantations. Therefore, although its biodiesel production is lower than that of oil palm, its cultivation pattern is considered more environmentally sustainable and has the potential to reduce ecological impacts.

Table 2. Comparison of cultivation conditions and biodiesel process operations for palm oil and *kemiri sunan*

Component	Palm Oil	Kemiri Sunan
Soil fertility	Fertile	Moderate to low; tolerant of less fertile land
Above-ground vegetation	Legumes	Intercropped as shade tree for coffee
Seedling source	Seeds	Seeds with top grafting
Plant density	136 ha^{-1}	±130 plants ha^{-1}
Intensity	Very intensive	Relatively lower compared to palm oil
Start of production	30 months	36 months
Edible / Non-edible	Edible	Non-edible
FFA value	< 2	< 3, with harvest treatment no more than 14 days after falling
Biodiesel production reaction	Transesterification	Transesterification
Biodiesel source	Palm mesocarp, palm kernel	*Kemiri sunan* kernel oil

In the biodiesel production process, both palm oil and *kemiri sunan* use transesterification reactions; however, they differ in terms of raw material characteristics. Palm oil generally has a lower free fatty acid (FFA) content, making its processing more straightforward. However, the use of edible crops as raw materials may create potential food-versus-fuel conflicts. In contrast, *kemiri sunan* utilizes non-edible kernel oil, with oil quality maintained through appropriate post-harvest handling practices. It also offers ecological advantages because it can be cultivated on marginal land and integrated into agroforestry systems. Although its productivity remains lower than that of palm oil, *kemiri sunan* has the potential to serve as a more environmentally sustainable biodiesel feedstock when supported by effective cultivation management and a well-organized supply chain.

Environmental Impact Analysis

The inventory data are divided into three parts, consisting of cultivation, fruit processing, and the B100 biodiesel production process.

Table 3. Kemiri Sunan Cultivation Inventory

No	Process	Component	Input/Output	Quantity per hectare	Unit	Data Source
1	Land Cultivation	Gasoline	Input	15	Liter	market for petrol, unleaded, burned in machinery | petrol, unleaded, burned in machinery | APOS, S
2	Grafting	Entres Scion	Input	130	Pcs	market for jatropha seed | jatropha seed | APOS, S
		Rootstock	Input	130	Pcs	market for tree seedling, for planting | tree seedling, for planting | APOS, S
		Fungicide	Input	65	Gram	market for pyrazole | pyrazole (fungicide)
		Insecticide	Input	13	Gram	market for pyrazole | pyrazole (Insecticide)
		Water	Input	26	Liter	market for tap water | tap water | APOS, S
3	Planting	Dolomite	Input	13	Kg	market for Dolomite | Dolomite |

						APOS, S
4	Fertilization	NPK Fertilizer	Input	521	kg	market for NPK (15-15-15) fertilizer | NPK (15-15-15) fertilizer | APOS, S
5	Harvesting	Fruits	Output	32621	Kg	Kemiri Sunan
6	Transportation	Transportation	Input	6	tkm	transport, freight, tractor and trailer, diesel, agricultural

Based on Table 3, cultivation activities begin with land preparation using 15 liters of gasoline, followed by grafting using 130 units of scions and rootstocks, along with 65 g of fungicide and 13 g of insecticide. The fertilization stage represents the largest input, consisting of 521 kg of NPK (15-15-15) fertilizer per hectare. The harvesting output was recorded as 32,621 kg of *kemiri sunan* fruit per hectare (Table 3). Note that a value of 6,688 kg was cited in the descriptive narrative; this figure represents the adjusted mass after post-harvest sorting and losses (approximately a 20.5% reduction). The authors are requested to verify and reconcile these figures explicitly in the final manuscript. The harvested fruit was transported over a distance of 6 tkm to the processing facility. All inventory data were sourced from the Ecoinvent APOS database, ensuring standardized and reproducible life cycle inventory (LCI) inputs.

Table 4. Fruit Processing Inventory Table

No	Process	Component	Input/Output	Quantity per hectare	Unit	Data Source
7	Stripping	PLN Electricity	Input	112.5	kWh	electricity production, lignite | electricity, high voltage | APOS, S
		Kernel	Output	7829	kg	Kernel
		Shell	Output	5545	kg	Compost {RoW} treatment of garden biowaste, home composting in heaps | Cut-off, U
		Skin waste	Output	19246	kg	Compost {RoW} treatment of garden biowaste, home composting in heaps | Cut-off, U
8	Drying	PLN Electricity	Input	672	kWh	electricity production, lignite | electricity, high voltage | APOS, S
		Kernel	Output	7000	kg	Kernel
		Water	Output	829	gram	Elementary

		vapor				flows/Emission to air/unspecified
9	Kernel Pressing	PLN Electricity	Input	102.5	kWh	electricity production, lignite | electricity, high voltage | APOS, S
		Kernel Oil	Output	3500	kg	Kernel oil
		Expeller	Output	3500	kg	Biowaste {RoW} treatment of biowaste, industrial composting | Cut-off, U

Table 4 presents technical data for the post-harvest stage, including stripping, drying, and kernel pressing processes. The highest electrical energy requirement is observed during the drying stage, reaching 672 kWh, while the stripping process generates a substantial amount of shell waste, totaling 3,946 kg. Overall, these data demonstrate the mass conversion efficiency from raw materials to the final product, namely 723 kg of kernel oil, along with by-products such as meal cake and shells.

Table 5. Biodiesel process inventory table

No	Process	Component	Input/Output	Quantity per hectare	Unit	Data Source
10	Transesterification	Methanol	Input	875	kg	market for methanol | methanol | APOS, S
		KOH	Input	35	kg	market for electrolyte, KOH, LiOH additive | electrolyte, KOH, LiOH | APOS, S
		Crude Oil	Output	3885	kg	Crude Oil
		PLN Electricity	Input	344	kWh	electricity production, lignite | electricity, high voltage | APOS, S
		Glycerol	Output	525	kg	glycerine distillate bottom
11	Washing	Water	Input	1250	liter	market for tap water | tap water | APOS, S
		PLN Electricity	Input	1.0	kWh	electricity production, lignite | electricity, high voltage | APOS, S
		Wastewater	Output	1438	liter	treatment of wastewater, average, wastewater treatment | wastewater, average | APOS, S
12	Bio additive Final	Biodiesel	Input	2975	kg	Biodiesel

Product	Bio Additive	Input	60	kg	tall oil, crude
	B100 Final Product	Output	3035	kg	B100 Final Product

Based on Table 5, the final stage of biodiesel production consists of transesterification, washing, and formulation of the final B100 product. In the transesterification stage, 875 kg of methanol and 3.5 kg of KOH are used to process 3,885 kg of crude oil, producing glycerol as a by-product. The washing stage requires a substantial amount of water (1,250 liters), generating 1,438 liters of wastewater, while electricity consumption across both stages is relatively low, totaling 344 kWh. The overall process concludes with the blending of biodiesel and bio-additives, resulting in 3,035 kg of ready-to-use B100 biodiesel.

LCIA of Kemiri Sunan

Table 6 presents eighteen environmental impact categories derived from data processing using OpenLCA with the ReCiPe 2016 v1.03 Midpoint (H) method. This method is an environmental impact assessment approach that translates various emissions and resource consumption data into impact categories, including climate change, toxicity, eutrophication, and land use. The method applies the Hierarchist (H) perspective, which is considered a balanced approach and is widely adopted in Life Cycle Assessment (LCA) studies.

Table 6. LCIA table for kemiri sunan

No	Impact Category	Result	Unit
1	Acidification: terrestrial	0,01	kg SO2-Eq
2	Climate change	2,04	kg CO2-Eq
3	Ecotoxicity: freshwater	0,10	kg 1,4-DCB-Eq
4	Ecotoxicity: marine	0,13	kg 1,4-DCB-Eq
5	Ecotoxicity: terrestrial	1,89	kg 1,4-DCB-Eq
6	Energy resources: non-renewable, fossil	0,60	kg oil-Eq
7	Eutrophication: freshwater	0,00	kg P-Eq
8	Eutrophication: marine	0,00	kg N-Eq
9	Human toxicity: carcinogenic	0,26	kg 1,4-DCB-Eq
10	Human toxicity: non-carcinogenic	3,55	kg 1,4-DCB-Eq
11	Ionising radiation	0,01	kBq Co-60-Eq
12	Land use	0,15	m2*a crop-Eq
13	Material resources: metals/minerals	0,04	kg Cu-Eq
14	Ozone depletion	0,00	kg CFC-11-Eq
15	Particulate matter formation	0,04	kg PM2.5-Eq
16	Photochemical oxidant formation: human health	0,01	kg NOx-Eq
17	Photochemical oxidant formation: terrestrial ecosystem	0,01	kg NOx-Eq
18	Water use	0,25	m3

The results show that climate change, non-carcinogenic human toxicity, and terrestrial ecotoxicity are the three dominant impact categories. The climate change impact (2.04 kg CO_2-eq per liter) is primarily driven by PLN/lignite-based electricity consumption during the drying (672 kWh), transesterification (344 kWh), and stripping (112.5 kWh) stages, combined with N_2O emissions from synthetic NPK fertilizer application. Terrestrial ecotoxicity (1.89 kg 1,4-DCB-Eq) arises mainly from pesticide use (fungicides and insecticides) and trace heavy metal emissions associated with coal combustion. Non-carcinogenic human toxicity (3.55 kg 1,4-DCB-Eq) is dominated by methanol inputs during transesterification and metal emissions from lignite-based electricity generation.

The use of fossil resources (0.60 kg oil-Eq) reflects the remaining dependence on non-renewable energy sources within the production system. Land use (0.15 m^2·a crop-Eq) and water consumption (0.25 m^3) represent the lowest impact categories, reflecting *kemiri sunan*'s compatibility with low-intensity cultivation systems on marginal lands. The carbon emission value of 2.04 kg CO_2-eq per liter is lower than the 3.99 kg CO_2-eq reported by Sucahyo (2025), which can be attributed to the exclusion of the esterification process and the incorporation of updated 2026 field data.

Comparison of Environmental Impacts of Diesel Oil, Palm Oil, and Kemiri Sunan

Figure 4 demonstrates that all biodiesel alternatives generate lower climate change impacts than fossil diesel. Palm oil biodiesel (1,659 kg CO_2-eq/ton) achieves the lowest emissions among the three alternatives, followed by *kemiri sunan* biodiesel (1,802 kg CO_2-eq/ton), whereas fossil diesel (3,400 kg CO_2-eq/ton) remains the highest. The slightly higher emissions of *kemiri sunan* biodiesel compared with palm oil biodiesel are attributable to its more energy-intensive drying process and lower oil-to-fruit conversion ratio, both of which increase electricity consumption per unit of biodiesel produced. Nevertheless, *kemiri sunan* biodiesel achieves a 47.0% reduction in emissions compared with fossil diesel, confirming its potential as a meaningful contributor to transport sector decarbonization (Gielen et al., 2019). This comparison highlights the importance of improving process efficiency, particularly in drying operations and electricity sourcing, to enhance the environmental competitiveness of *kemiri sunan* biodiesel relative to palm oil biodiesel.

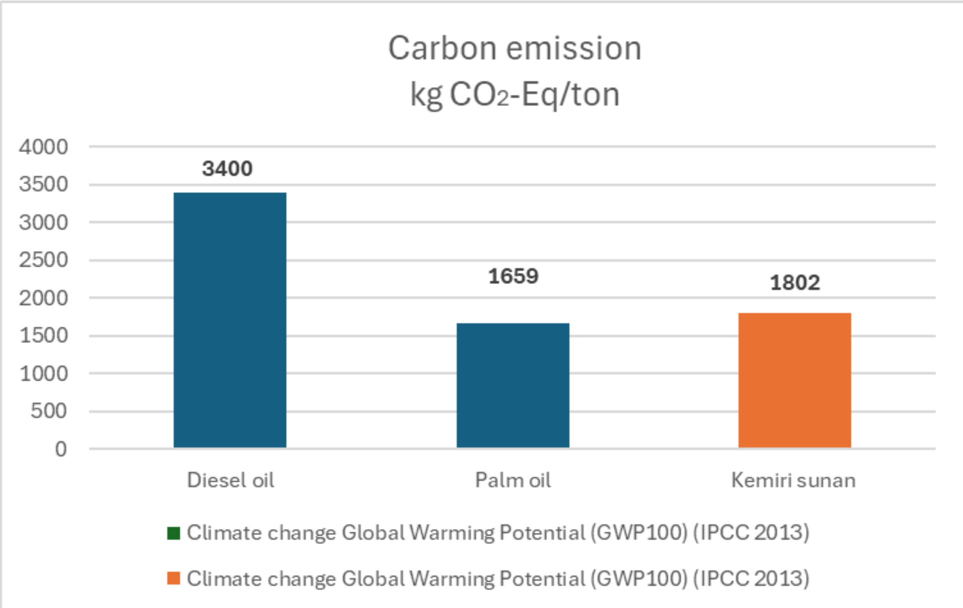

Figure 4. Comparison of emissions from Diesel, Palm Oil, and Kemiri Sunan

Emission Reduction Scenario for the Category of Replacing the Electricity Source

In the analysis of *kemiri sunan* as a *Nature-Based Solution*, the focus is directed toward the climate change indicator, where the LCA results show emissions of 2.04 kg CO_2-eq per functional unit of 1 liter of B100 biodiesel produced on 1 hectare of land containing 512 trees. One of the main emission contributors is the use of PLN electricity generated from lignite-based sources. Therefore, modelling was conducted using Ecoinvent 3.11 and the IPCC 2013 impact assessment method by replacing the PLN electricity source with solar photovoltaic (solar PV)-based electricity to evaluate the potential for carbon emission reduction within the *kemiri sunan* biodiesel production system.

The modelling of the transition in electricity supply from PLN-based electricity to solar PV aims to strengthen the sustainability aspects of the system. Based on the analysis presented in Graph 6, this transition is projected to significantly reduce carbon emissions by up to 56%, decreasing emissions from 2.02 kg CO_2-eq to 0.74 kg CO_2-eq. By adopting this proposal, BRMP TRI has the opportunity to achieve more ambitious climate change mitigation targets through the measurable integration of renewable energy sources.

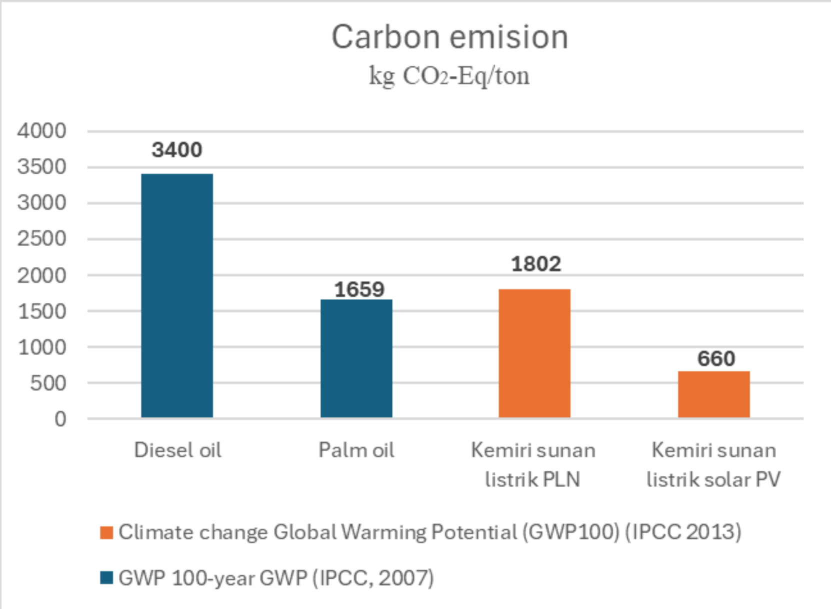

Figure 5. Comparison of carbon emissions: Diesel, Palm Oil, Kemiri Sunan with PLN electricity and solar PV

Energy Balance Analysis

Analysis in Table 8 shows that the use of solar PV-based electricity significantly reduces the Cumulative Energy Demand (CED) from 29.68 MJ-eq to 21.25 MJ-eq, representing a reduction of approximately 28%. This decrease is mainly attributed to the lower consumption of non-renewable energy, which dominates the PLN/lignite electricity scenario. Although the contribution of renewable energy increases in the solar PV scenario, the overall system becomes more efficient due to greater reductions in fossil energy consumption. Therefore, the use of solar PV electricity is considered more energy-efficient and supports the sustainable operation of biodiesel production.

Table 8. Comparison of NEG, NER, and SEC

Energy Balance	CED PLN/Lignite Electricity	CED Solar PV Electricity	Reference Paper	Unit
Cumulative Energy Demand (CED)	29.68	21.25		MJ-Eq
Density			892	kg/m^3
Calorific Value of Kemiri Sunan			40.098	MJ/kg
Calorific Value of Kemiri Sunan per liter			35.77	MJ/liter
Net Energy Gain (NEG)	6.09	14.5		MJ-Eq
Net Energy Ratio (NER)	1.21	1.68		
Specific Energy Consumption	29.68	21.25		MJ/liter

(SEC)	

The energy balance analysis shows that the use of Solar PV electricity is more efficient than PLN/lignite-based electricity in the biodiesel production process. This is demonstrated by the reduction in the Cumulative Energy Demand (CED) value, improvement in Net Energy Gain (NEG), and increase in the Net Energy Ratio (NER) toward 1, indicating a more sustainable system with reduced dependence on fossil energy sources. Additionally, the utilization of renewable energy reduces Specific Energy Consumption (SEC) and improves the overall thermodynamic efficiency of the system.

Carbon Payback Period

Based on Figure 8a and Figure 8b, the use of Solar PV electricity demonstrates better Carbon Payback Period (CPP) performance compared with PLN electricity in the *Zelkova serrata* carbon sequestration model. In the PLN scenario, operational emissions of 2.02 kg CO_2-eq cause the carbon balance curve to remain in the negative region until the CPP is achieved in the 11th year, with a cumulative carbon deficit reaching approximately −2.04. Conversely, in the Solar PV scenario, emissions decrease to 0.74 kg CO_2-eq, allowing the CPP to be achieved earlier, within the 6th year. These results indicate that the integration of low-carbon energy sources through Solar PV technology can accelerate the carbon payback period while enhancing the effectiveness of carbon sequestration within the Nature-Based Solutions (NBS) strategy.

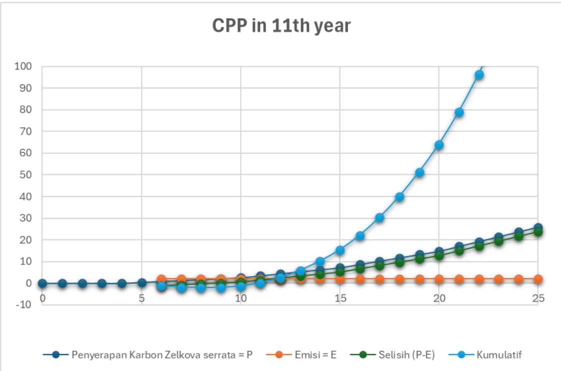

Figure 6. CPP of carbon emissions from electricity PLN against Zelkova serrata sequestration

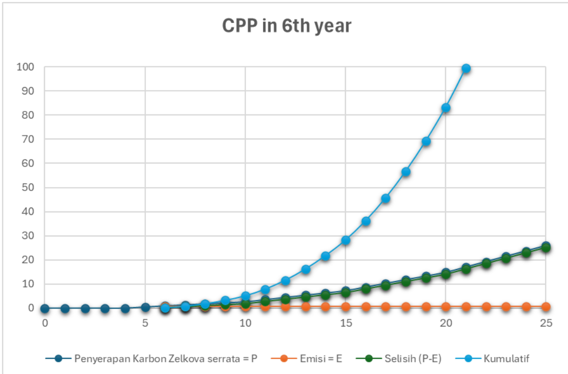

Figure 7. CPP of carbon emissions from solar PV against Zelkova serrata sequestration

These results indicate that the effectiveness of Nature-Based Solutions (NbS) is strongly influenced by the compatibility between the biological characteristics of the species and climate policy targets. Therefore, combining fast-growing species for accelerated decarbonization with slow-growing species for ecosystem stability represents an optimal strategy for minimizing carbon debt and enhancing sustainable environmental benefits.

Discussion

This research demonstrates the environmental potential of B100 biodiesel derived from *kemiri sunan* (*Reutealis trisperma*) as a bioenergy source aligned with the Nature-Based Solutions (NbS) concept, assessed through Life Cycle Assessment (LCA) and energy balance analysis. The non-edible characteristics of kemiri sunan, its tolerance to marginal and degraded lands, and its compatibility with agroforestry systems position it as an ecologically sound alternative that does not directly compete with food supply chains. This characteristic is consistent with the sustainable development paradigm, which emphasizes the integration of energy production, environmental conservation, and resource management (Hajian & Kashani, 2021; Nesshöver et al., 2017).

Furthermore, the high oil content of *kemiri sunan* kernels and its adaptability to low-fertility soils strengthen its prospective role as an alternative bio-oil source in Indonesia (Herman et al., 2023). The cultivation system analyzed at BRMP TRI, which employs a hybrid reactor process with two-stage transesterification, represents a scalable production model with potential for national replication, particularly on marginal lands.

The results showed that the *kemiri sunan* cultivation system exhibits different ecological characteristics compared with oil palm. Oil palm has higher biodiesel productivity but requires fertile land and intensive management practices that may increase environmental pressure. In contrast, *kemiri sunan* demonstrates greater tolerance to less fertile land and can be developed through agroforestry systems or intercropping practices as a shade plant for coffee cultivation. This approach supports landscape ecological functions and has the potential to reduce environmental degradation, as described in the concept of agroforestry-based solutions for climate change mitigation (Hernández-Morcillo et al., 2018). Additionally, because *kemiri sunan* is a non-edible plant, its development does not generate food-versus-energy conflicts, which commonly occur with biodiesel derived from edible vegetable oils. This strengthens the position of *kemiri sunan* as a more sustainable second-generation biodiesel feedstock (Tibesigwa et al., 2023).

The life cycle inventory analysis revealed that cultivation and fruit processing stages are the primary contributors to energy consumption and environmental emissions. During the cultivation stage, NPK fertilizer application (521 kg/ha) represents the largest material input and a significant indirect source of N_2O emissions through soil nitrification processes, consistent with the findings of Lovasz (2023) regarding fertilization-driven emissions in biodiesel crops. During the fruit processing stage, the drying process (672 kWh) dominates electricity consumption due to the moisture reduction requirements necessary to achieve kernel quality standards.

Based on the Life Cycle Impact Assessment (LCIA) results, the ReCiPe 2016 Midpoint (H) method effectively identified electricity consumption and synthetic fertilizer application as the primary environmental hotspots, confirming the importance of these parameters in emission reduction strategies. The selection of an LCIA method directly influences the identification and prioritization of environmental hotspots Sala (2020) and Huijbregts (2017), highlighting the methodological significance of this study's approach.

One of the key mitigation strategies evaluated was the replacement of PLN/lignite-based electricity with solar photovoltaic (Solar PV) energy. The modeling results demonstrated a 63% reduction in climate change impact, decreasing from 2.02 to 0.74 kg CO_2-eq, accompanied by improvements in Cumulative Energy Demand (CED) and Net Energy Ratio (NER). These findings reinforce the results of Haase (2022), which indicate that renewable energy integration significantly improves overall bioenergy sustainability performance. Within the context of Indonesia’s global energy transition commitments, increasing renewable energy penetration in the biofuel sector represents an important decarbonization pathway (Gielen et al., 2019; GSR 2025).

From an economic perspective, the adoption of Solar PV for biodiesel production in Indonesia presents both opportunities and challenges. Indonesia’s geographic location within the solar irradiation belt, with an average solar irradiation level of 4.5–5.5 kWh/m^2/day, provides favorable conditions for cost-effective solar energy generation. However, the initial capital investment required for Solar PV systems (approximately USD 0.5–1.5 per watt of installed capacity) remains a significant barrier for small- and medium-scale producers such as BRMP TRI. Government incentive mechanisms, including the Renewable Energy Certificate (REC) scheme, net-metering policies, and green investment financing, could substantially reduce the economic payback period of Solar PV investments. A dedicated techno-economic feasibility analysis is recommended as a priority area for future research to evaluate the financial viability of *Solar PV* integration at an operational scale in *kemiri sunan* biodiesel facilities.

The Carbon Payback Period (CPP) analysis demonstrated that Solar PV integration accelerates the CPP from 11 to 6 years by reducing annual production emissions from 2.02 to 0.74 kg CO_2-eq, highlighting the critical role of energy decarbonization in enhancing NbS effectiveness. As Chun (2026) emphasized, the LCA approach for NbS is essential for evaluating the balance between operational emissions and long-term carbon sequestration capacity. Changes in plant growth rates also influence carbon sequestration capacity as trees mature Jo (2017), suggesting that CPP values are dynamic and improve throughout the plantation lifetime. Cook (2020) further demonstrated that carbon accumulation rates from natural forest regrowth are highly species-and site-specific, reinforcing the importance of selecting ecologically appropriate species for NbS carbon accounting.

Regarding energy balance, the Net Energy Gain (NEG) values of 6.09 MJ-eq (PLN) and 14.5 MJ-eq (Solar PV), along with corresponding Net Energy Ratio (NER) values of 1.21 and 1.68, confirm that *kemiri sunan* B100 biodiesel production is energy-positive under both scenarios. These values are consistent with previous second-generation biodiesel studies. Tibesigwa (2023) reported NER values ranging from 1.15 to 1.45 for non-edible feedstocks, including *Jatropha curcas* and *Calophyllum inophyllum*, while Sucahyo (2025) recorded an NER value of 1.19 for the same *kemiri sunan* feedstock. The *Solar PV* scenario's NER value of 1.68 represents a substantial improvement, indicating that renewable energy adoption not only reduces emissions but also enhances the thermodynamic efficiency of the biodiesel production system. The reduction in specific energy consumption (*SEC*) from 29.68 to 21.25 MJ/liter further confirms the energy savings achievable through electricity transition.

CONCLUSION

This study establishes that B100 biodiesel from *kemiri sunan* (*Reutealis trisperma*) is a viable non-edible bioenergy alternative, with a life cycle carbon emission of 2.04 kg CO_2-eq per liter, which is significantly lower than that of fossil diesel (3,400 kg CO_2-eq/ton) and competitive with palm oil biodiesel. The integration of solar PV electricity reduced production emissions by 56% (to 0.74 kg CO_2-eq) and shortened the Carbon Payback Period from 11 to 6 years, confirming the critical role of renewable energy integration in enhancing biodiesel sustainability. The energy balance analysis (NER: 1.21 with PLN electricity and 1.68 with solar PV) confirms the thermodynamic viability of the system. The principal novelty of this research lies in the simultaneous integration of Life Cycle Assessment (LCA), energy balance assessment, and Carbon Payback Period analysis within a Nature-Based Solutions framework—an approach that has not previously been applied to *kemiri sunan* biodiesel and provides a replicable model for evaluating non-edible bioenergy sustainability.

From a practical standpoint, *kemiri sunan* biodiesel offers a sustainable pathway for Indonesia's energy transition by utilizing degraded marginal lands without competing with food supply chains. To maximize implementation potential, future research should prioritize: (1) techno-economic feasibility assessments of solar PV integration at the BRMP TRI scale; (2) reduction of fertilization-related emissions through organic nutrient management strategies; (3) development of Carbon Payback Period models using native Indonesian carbon-sequestering species; and (4) national-scale supply chain assessments for *kemiri sunan* biodiesel. These priorities collectively support the achievement of Indonesia's Nationally Determined Contribution (NDC) targets through the synergistic deployment of non-edible biofuels and Nature-Based Solutions.

ACKNOWLEDGEMENT

The authors express their gratitude to the Balai Perakitan dan Pengujian Tanaman Industri dan Penyegar (BRMP TRI), Ministry of Agriculture, Parung Kuda, Sukabumi, Indonesia, for providing access to research facilities, operational data, and technical support throughout this study. The authors also thank the research team and field officers at BRMP TRI for their assistance during data collection.

AUTHOR CONTRIBUTION STATEMENT

Author 1: Conceptualization, Data Curation, Formal Analysis, Methodology, Writing – Original Draft. Author 2: Supervision, Validation, & Editing.

REFERENCES

Azadi, H., Barati, A. A., Nazari Nooghabi, S., & Scheffran, J. (2022). Climate-related disasters and agricultural land conversion: Towards prevention policies. *Climate and Development*, *14*(9), 814–828. https://doi.org/10.1080/17565529.2021.2008291

Chun, Y., Kim, I., & Jeon, E.-C. (2026). Evaluating the Carbon Payback Period of Nature-Based Solutions: A Life Cycle Assessment Approach. *Nature-Based Solutions*, 100310.

https://doi.org/10.1016/J.NBSJ.2026.100310
Cook-Patton, S. C., Leavitt, S. M., Gibbs, D., Harris, N. L., Lister, K., Anderson-Teixeira, K. J., Briggs, R. D., Chazdon, R. L., Crowther, T. W., & Ellis, P. W. (2020). Mapping carbon accumulation potential from global natural forest regrowth. *Nature*, *585*(7826), 545–550. https://doi.org/10.1038/s41586-020-2686-x
Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., & Gorini, R. (2019). The role of renewable energy in the global energy transformation. *Energy Strategy Reviews*, *24*, 38–50. https://doi.org/10.1016/j.esr.2019.01.006
Global Temperature - Earth Indicator - NASA Science. (2021). Retrieved November 12, 2025, from https://science.nasa.gov/earth/explore/earth-indicators/global-temperature/
GSR 2025 | RENEWABLE ENERGY IN TRANSPORT. (2025). Retrieved November 12, 2025, from https://www.ren21.net/gsr-2025/sectors/transport/
Haase, M., Wulf, C., Baumann, M., Rösch, C., Weil, M., Zapp, P., & Naegler, T. (2022). Prospective assessment of energy technologies: a comprehensive approach for sustainability assessment. *Energy, Sustainability and Society*, *12*(1), 20. https://doi.org/10.1186/s13705-022-00344-6
Hajian, M., & Kashani, S. J. (2021). Evolution of the concept of sustainability. From Brundtland Report to sustainable development goals. In *Sustainable resource management* (pp. 1–24). Elsevier. https://doi.org/10.1016/B978-0-12-824342-8.00018-3
Herman, M., Hafif, B., Ferry, Y., Aunillah, A., Firdaus, N. K., Listyati, D., & Pranowo, D. (2023). The prospect of kemiri sunan (Reutalis trisperma B. airy shaw) development as a source of bio-oil from inedible crops. *E3S Web of Conferences*, *373*, 4017. https://doi.org/10.1051/e3sconf/202337304017
Hernández-Morcillo, M., Burgess, P., Mirck, J., Pantera, A., & Plieninger, T. (2018). Scanning agroforestry-based solutions for climate change mitigation and adaptation in Europe. *Environmental Science & Policy*, *80*, 44–52. https://doi.org/10.1016/j.envsci.2017.11.013
Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & Van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment*, *22*(2), 138–147. https://doi.org/10.1007/s11367-016-1246-y
Jo, H.-K., & Park, H.-M. (2017). Changes in growth rate and carbon sequestration by age of landscape trees. *Journal of the Korean Institute of Landscape Architecture*, *45*(5), 97–104. https://doi.org/10.9715/KILA.2017.45.5.097
Kao, Y.-L., & Chen, J.-Y. (2025). Exploring the Purchase Intention of Electric Vehicles Through the UTAUT 2 Model. *2025 1st International Conference on Consumer Technology (ICCT-Pacific)*, 1–2. https://doi.org/10.1109/ICCT-PACIFIC63901.2025.11012759
Lovasz, A., Sabau, N. C., Borza, I., & Brejea, R. (2023). Production and quality of biodiesel under the influence of a rapeseed fertilization system. *Energies*, *16*(9), 3728. https://doi.org/10.3390/en16093728
Nesshöver, C., Assmuth, T., Irvine, K. N., Rusch, G. M., Waylen, K. A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., & Kovacs, E. (2017). The science, policy and practice of nature-based solutions: An interdisciplinary perspective. *Science of the Total Environment*, *579*, 1215–1227. https://doi.org/10.1016/j.scitotenv.2016.11.106
Sala, S., Laurent, A., Vieira, M., & Van Hoof, G. (2020). Implications of LCA and LCIA choices on interpretation of results and on decision support. *The International Journal of Life Cycle Assessment*, *25*(12), 2311–2314. https://doi.org/10.1007/s11367-020-01845-2
Siregar, K., Tambunan, A. H., Irwanto, A. K., Wirawan, S. S., & Araki, T. (2015). A comparison of life cycle assessment on oil palm (Elaeis guineensis Jacq.) and physic nut (Jatropha curcas Linn.) as feedstock for biodiesel production in Indonesia. *Energy Procedia*, *65*, 170–179. https://doi.org/10.1016/j.egypro.2015.01.054
Sucahyo, L., Ardelia, L. P., Purwanti, N., & Virgian, S. (2025). Energy Balance Analysis and Life Cycle Assessment (LCA) of Biodiesel Production from Philippine Tung (Reutealis trisperma) Oil in Indonesia. *IOP Conference Series: Earth and Environmental Science*, *1513*(1), 12019. https://doi.org/10.1088/1755-1315/1513/1/012019
Tibesigwa, T., Iezzi, B., Lim, T. H., Kirabira, J. B., & Olupot, P. W. (2023). Life cycle assessment of biodiesel production from selected second-generation feedstocks. *Cleaner Engineering and*

Technology, *13*, 100614. https://doi.org/10.1016/J.CLET.2023.100614
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8