

Life Cycle Assessment (LCA) of Biodiesel Production from Coconut Pulp Using In-Situ Transesterification with Microwave Energy

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ABSTRACT

Coconut pulps are solid waste from coconut processing that has had its coconut milk extracted, with a remaining oil content of around 12.2–15.9%. The processing of coconut pulp is not yet optimal, and this waste has the potential to be utilized as renewable energy in the form of biodiesel. Biodiesel is produced through an in-situ transesterification process assisted by microwave energy. This study aims to identify the potential environmental impacts of biodiesel production from coconut pulp as fuel. A Life Cycle Assessment (LCA) was conducted using the cradle-to-gate approach with the SimaPro ver. 9.4.0.3 data processing application and a database similar to the eco-invent database. The environmental impact assessment was analyzed using the EF 3.0 Method (adapted) V1.03 / EF 3.0 normalization and weighting set. The results show that among the stages of the biodiesel production process, the transportation of raw materials and supporting materials has the greatest impact on climate change compared to other stages. The transportation stage contributed 78.19 kg CO₂-eq out of a total of 204.35 kg CO₂-eq in the climate change category and dominated energy resource use at 1108.14 MJ out of a total of 1742.17 MJ. In addition, the preparation stage also contributed significantly to climate change, with emissions reaching 56.21 kg CO₂-eq. The large contribution from the transportation stage was mainly caused by exhaust gas emissions from vehicles used to transport raw materials and supporting materials. Based on the LCA results, environmental performance improvements or continuous improvements that can be implemented include optimizing logistics, regulating fuel use, selecting the nearest sources of raw materials, and improving energy efficiency during the preparation stage to support more sustainable biodiesel production from coconut pulp.



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A. INTRODUCTION

Energy consumption is one way to assess a nation's economic growth, progress, and welfare (Rajesh et al., 2020). Global primary energy consumption increased to around 5.8% during 2021, almost double the energy consumption rate of the previous three years. In Indonesia alone, primary energy consumption was around 2.9% during 2021 (*Bp Statistical Review of World Energy*, 2022). Recently, concerns about the environment, rising prices, and fuel scarcity have driven interest in the development of alternative sources of petroleum-based diesel fuel with a particular emphasis on renewable natural resources (Rajesh et al., 2020), (*Bp Statistical Review of World Energy*, 2022), (Azad et al., 2016), (Nabgan et al., 2022). Alternative fuels to petroleum must be technically feasible, economically competitive, environmentally acceptable, readily available, and not cause competition between food and fuel sources (Zareh et al., 2017). Therefore, efforts are needed to develop renewable and environmentally friendly alternative energy sources. The alternative fuel that is widely developed today is biodiesel (Hartulistiyoso et al., 2024), (Bow et al., 2022).

Biodiesel is a monoalkyl ester compound produced from triglycerides through the esterification of free fatty acids with methanol or ethanol ester and glycerol (Hartulistiyoso et al., 2024), (Irawan et al., 2021). Biodiesel is considered more environmentally friendly since it generates cleaner exhaust emissions compared to conventional diesel or fossil-based fuels (Hartulistiyoso et al., 2024), (Moulita & Kalsum, 2020). One type of biomass that can be used as raw material for biodiesel production is coconut pulp. Coconut pulps are solid waste from coconut processing after the coconut milk has been extracted. Coconut pulp still contain around 12.2-15.9% oil (Hartulistiyoso et al., 2024), (N. S. Putri et al., 2022). The processing of coconut pulp is not yet optimal. It is usually only used as animal feed or left to mold and rot. Therefore, it is necessary to utilize coconut pulp into products with higher value. One of the uses that can be done is to convert coconut pulp into an alternative energy source, namely biodiesel. This step is a positive move towards diversifying products from coconut processing (N. S. Putri et al., 2022), (Kabul et al., 2022) and will increase the usefulness of coconut themselves. In general, the biodiesel production process involves extraction, purification, and esterification-transesterification of oil into biodiesel. These lengthy stages result in low efficiency and high energy consumption, which leads to high biodiesel production costs. Therefore, it is necessary to develop a more effective, efficient, and energy-saving biodiesel production process through in-situ transesterification with the help of microwave radiation (Hartulistiyoso et al., 2024), (Yunsari et al., 2019), (Yusi, 2018). In-situ transesterification is a simplification of the conventional process by eliminating the extraction and esterification processes so that the biodiesel production process can be shortened (Hartulistiyoso et al., 2024), (Mahlinda & Djafar, 2016). The conversion process of coconut pulp biomass can have an environmental impact that needs to be studied in the future. Life Cycle Assessment (LCA) is a systematic approach used to evaluate and predict the environmental sustainability of a product or process throughout its entire life cycle. This method objectively assesses potential environmental impacts by identifying and quantifying energy and material inputs, as well as emissions and waste released into

the environment, while also highlighting opportunities for environmental improvement (Wulandari et al., 2022), (Darojat et al., 2019). A comprehensive LCA study, covering all stages from initial processing to final utilization, provides a valuable framework for supporting decision-making in the development and implementation of biomass energy conversion technologies.

Coconut (*Cocos nucifera* L.) is a single seeded palm species with significant economic and technological potential. The coconut tree is classified as a multifunctional biomass resource, as almost all of its components including roots, trunk, leaves, and fruit can be utilized as raw materials for various industrial, agricultural, and energy-related applications. Owing to this extensive usability, *Cocos nucifera* is commonly referred to as the "tree of life". Coconut pulp is a by-product of coconut milk production. This agricultural waste is available in large quantities and has not been optimally utilized. Coconut pulp, which is a solid waste from coconut processing after the coconut milk has been extracted, still contains about 12.2-15.9% oil (Rajesh et al., 2020), (Kabul et al., 2022). Transesterification is defined as a reaction between alcohol and triglycerides to form alkyl esters and glycerol. These alkyl esters are called biodiesel. Meanwhile, triglycerides are the main components of oils and fats, which are triesters of glycerol with fatty acids (Budiman et al., 2018), (Amit, n.d.). The production of biodiesel using coconut pulp as a feedstock has been investigated and reported by numerous researchers. In-situ transesterification using microwaves is one of the processes that can be used to produce biodiesel (Syarif et al., 2020), (M. Putri et al., 2021). In-situ transesterification is a reaction that forms esters and glycerol from triglycerides and alcohol directly from the triglyceride source, not from extracted oil. Based on this study, the outcomes of Life Cycle Assessment (LCA) provide valuable insights for reducing environmental pollution and improving energy efficiency, thereby supporting the sustainability of biodiesel production processes and aligning with government policies aimed at lowering greenhouse gas (GHG) emissions (Han et al., 2019), (Utarina et al., 2022), (Wiloso et al., 2019).

Biodiesel made from palm oil generally faces environmental issues such as land-use change, deforestation, and high greenhouse gas emissions during the palm oil cultivation stage. Meanwhile, biodiesel from used cooking oil places greater emphasis on waste management and pollution reduction, but still requires oil extraction and purification processes before transesterification can take place.

The novelty of this study compared to previous research lies in the raw material used: coconut pulp, a solid waste product from coconut milk processing that has not been fully utilised but still contains 12.2–15.9% oil. Furthermore, the biodiesel production process is carried out using the microwave-assisted in-situ transesterification method, which integrates the extraction and transesterification processes into a single stage, making it simpler, more energy-efficient, and potentially reducing production costs compared to conventional methods. This study also emphasises environmental evaluation through an LCA approach across the entire process of converting coconut husk biomass into biodiesel, thereby providing a new perspective on the potential for utilising coconut waste as a more sustainable and environmentally friendly source of renewable energy.

B. METHODS

In this research, coconut pulp was utilized as the primary feedstock for biodiesel production via a microwave-assisted in-situ transesterification process, with crude glycerol generated as a by-product. In addition to evaluating the production process, an assessment of the associated environmental impacts was conducted using the Life Cycle Assessment (LCA) approach. The LCA framework was implemented in accordance with ISO 14040:2006 principles, which include (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) interpretation. The assessment was performed using SimaPro version 9.4.0.3 software, supported by the ecoinvent 3.0 database. This database served as a reference for modeling background processes, with data assumptions derived from processed primary data and supplemented by secondary data obtained from relevant and closely related literature (simapro manual PRe Consultants, 2008), (Alexander et al., 2021).

In addition, energy consumption data for microwave-assisted in-situ transesterification including electricity usage and process efficiency (such as raw material transport, raw material preparation, and in-situ transesterification using microwaves) was incorporated into the life cycle assessment to strengthen the generalisability and reliability of the sustainability evaluation results.

1. Purpose and Scope

The scope or limitations of the system used in this study is cradle to gate. Where the process begins from the material transport process to the biodiesel production process. Simapro models various stages of the biodiesel production life cycle consisting of transportation, preparation, and in-situ transesterification. This LCA analysis serves as an effective tool for identifying and quantifying the sustainability of natural resource utilization and environmental emissions, while also supporting the evaluation and implementation of potential environmental improvements in accordance with SNI ISO 14040:2016 and ISO 14044:2017 standards on environmental management (simapro manual PRe Consultants, 2008).

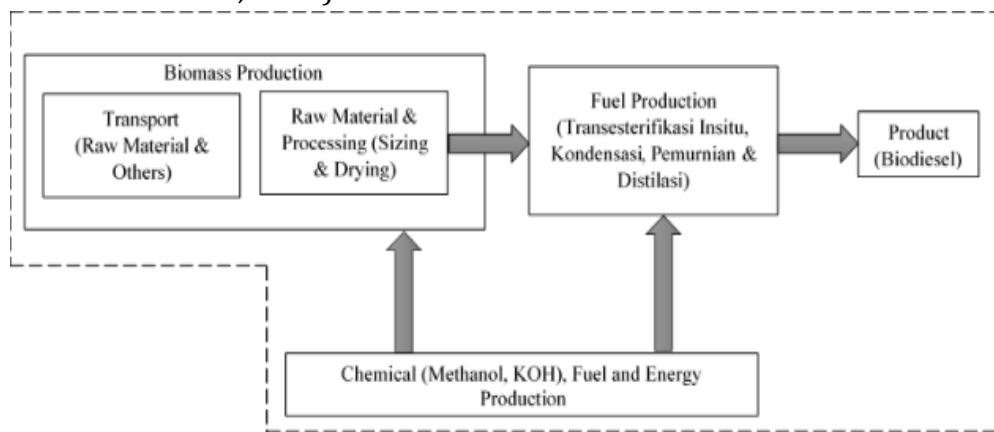


Figure 1. Scope of Cradle to Gate

2. LCA

This study focuses on the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) stages of biodiesel production. The LCI phase quantifies emissions generated

throughout the research activities, including transportation, feedstock preparation, and the in-situ transesterification process. The LCA modeling was performed using the SimaPro environmental modeling software version 9.4.0.3 (simapro manual PRe Consultants, 2008), (Wulandari et al., 2022).

3. Transportation

Raw materials and supporting materials were transported using private cars over a total distance of ± 13 km. The transportation of raw materials and other materials was modeled using passenger car data from the SimaPro database (simapro manual PRe Consultants, 2008), (Pré, 2014).

Table 1. Transport Inventory of Raw Materials

No	Input	Total	Unit
Material			
1.	Coconut Pulp	25	kg
2.	Methanol	10	lt
3.	KOH	10	lt
Energy			
1.	Diesel	10	lt
Emisi			
1.	CO	0.5	g/km
2.	NOx	0.08	g/km
3.	CO ₂	0.6	g/km

4. Preparation of Raw Material

The preparation of coconut pulp raw materials is carried out by drying the coconut pulp in a drying shed at a temperature of 35 °C until it reaches a constant weight and a size reduction of up to 60 mesh. A total of 10 kg of raw material was used, yielding 9.5 kg of ready-to-use raw material (Pré, 2014), (Utarina et al., 2022), (Wulandari et al., 2022).

Table 2. Inventory Preparation of Raw Materials

No	Input	Total	Unit
Material			
1.	Coconut Pulp	10	kg
Energy			
1.	Drying Shed	18	kWh
Product			
1.	Dried Coconut Pulp	9.5	kg

5. Transesterification In-Situ

In-situ transesterification using dried coconut pulp with a size of 60 mesh. The in-situ transesterification process takes place at a temperature of 60 °C with variations in time of 30, 60, and 90 minutes. The gas produced from the transesterification process is condensed using a condenser located above the microwave. The following is an overview of the in-situ transesterification apparatus with microwaves (Mahlinda & Djafar, 2016), (Putra et al., 2018).

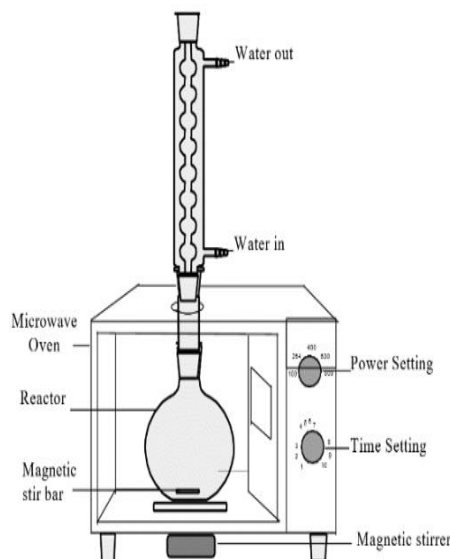


Figure 2. In-Situ Transesterification Device Scheme with Microwaves (Suryanto et al., 2015)

Table 3. Transesterification Inventory of Coconut Pulp

No	Input	Total	Unit
Material			
1.	Coconut Pulp	10	kg
2.	Methanol	5	lt
3.	KOH	5	lt
Energy			
1.	Microwave	1	kWh
2.	Condenser	0.7	kWh
3.	Distillation	0.7	kWh
Product			
1.	Biodiesel	8	lt

C. RESULT AND DISCUSSION

1. Life Cycle Investment (LCI)

The production of biodiesel from coconut pulp using in-situ transesterification with microwave energy process involves raw material transportation, preparation, and transesterification, which yields biodiesel and crude glycerol. Based on the

inventory results, the transportation process has the greatest environmental impact due to fuel consumption and raw material distribution.

Compared to biodiesel from palm oil, coconut pulp biodiesel has a lower environmental impact because it uses biomass waste, thus eliminating the need for cultivation, fertilizers, and land-use changes. Additionally, the microwave method is more efficient than conventional methods due to faster reaction times and lower energy requirements. The data used in this LCI comes from literature studies. Details of the impact categories can be seen below (Pré, 2014).

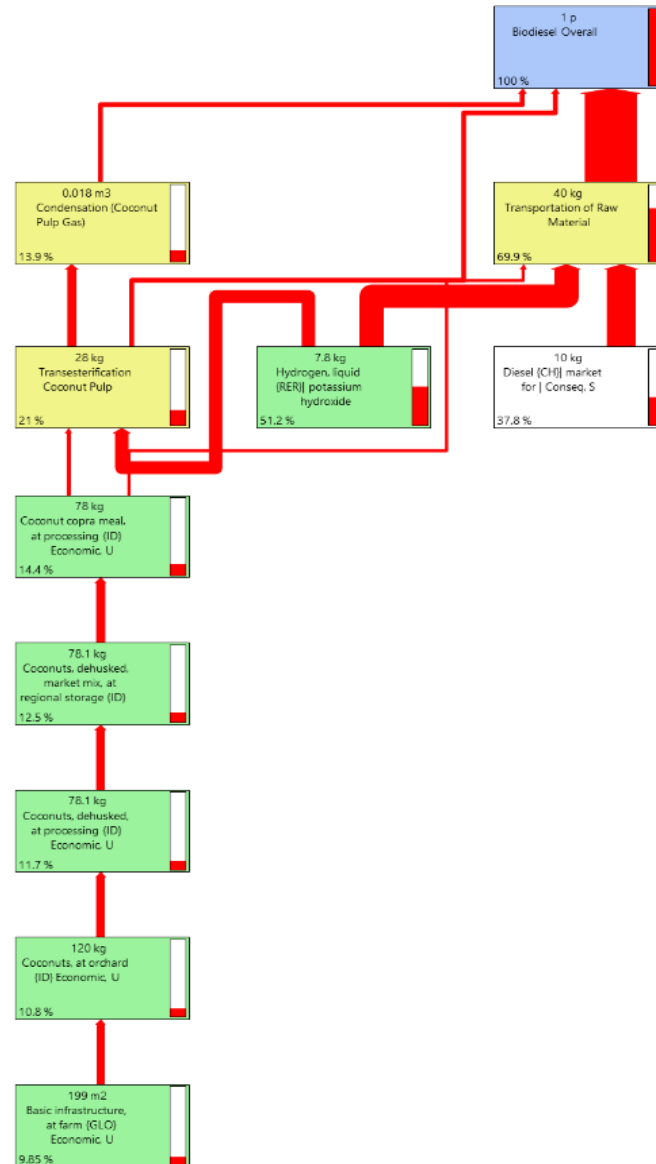


Figure 3. Inventory of Biodiesel Production Networks

2. LCIA

Once the life cycle inventory network is established, the processes with the highest contributions to environmental impacts are identified. The inventory data are analyzed using SimaPro version 9.4.0.3, applying the EF 3.0 Method (adapted) V1.03 with normalization and weighting procedures based on the EF 3.0 framework (simapro manual PRe Consultants, 2008).

3. Impact Assessment Characterization Analysis

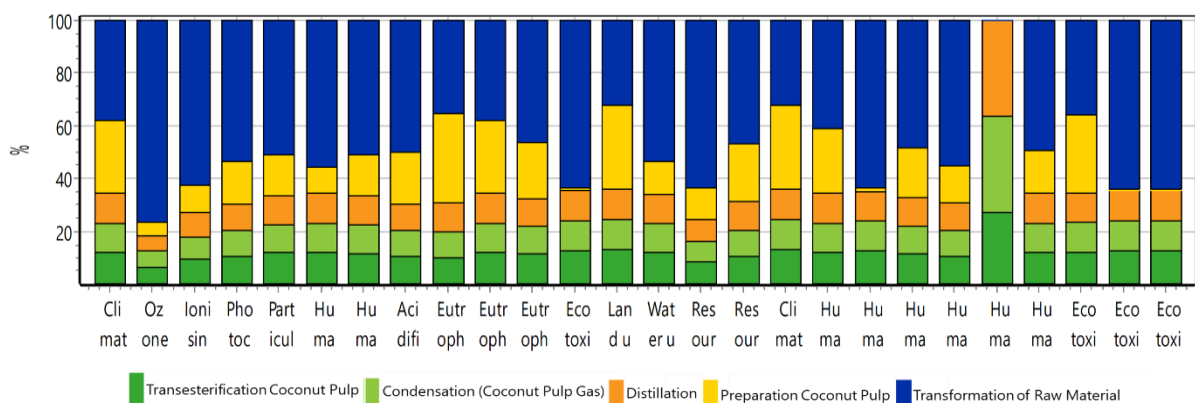
In the impact assessment characteristics section, each part of the process chain has a different impact on the environment. The following is an analysis of the impact characteristics of the biodiesel production process shown in Table 4, with 12 categories for each process. The values shown cannot yet be confirmed as to which part has the greatest impact on the overall process, given that the units for each impact vary. However, when viewed through the characterization graph shown in Figure 4, it is the transportation process that has the greatest impact on climate change, as indicated by the percentage indicator. This impact stems from fuel consumption during the distribution of raw materials to the production site.

Nevertheless, when compared to palm oil-based biodiesel, the environmental impact of coconut pulp biodiesel remains relatively lower because it does not involve the cultivation and processing stages of crude palm oil (CPO), which generate significantly higher greenhouse gas emissions. Furthermore, compared to conventional transesterification methods, the use of microwave-assisted in-situ transesterification technology results in a lower environmental impact due to shorter heating times and higher energy efficiency.

4. Weighting and Single Score Analysis

Biodiesel Production from coconut pulp shown in Figure 5 has the greatest impact on water ecotoxicity. This can be caused by the methanol solution used in the transesterification process and crude glycerol, which, if disposed of freely into the environment without further waste treatment, can have a significant impact.

Compared to palm oil-based biodiesel and conventional transesterification methods, coconut pulp biodiesel still has a lower overall environmental impact. This is because the raw material used comes from biomass waste, thereby reducing the environmental burden associated with the cultivation stage, and because the use of microwave technology is more energy-efficient.

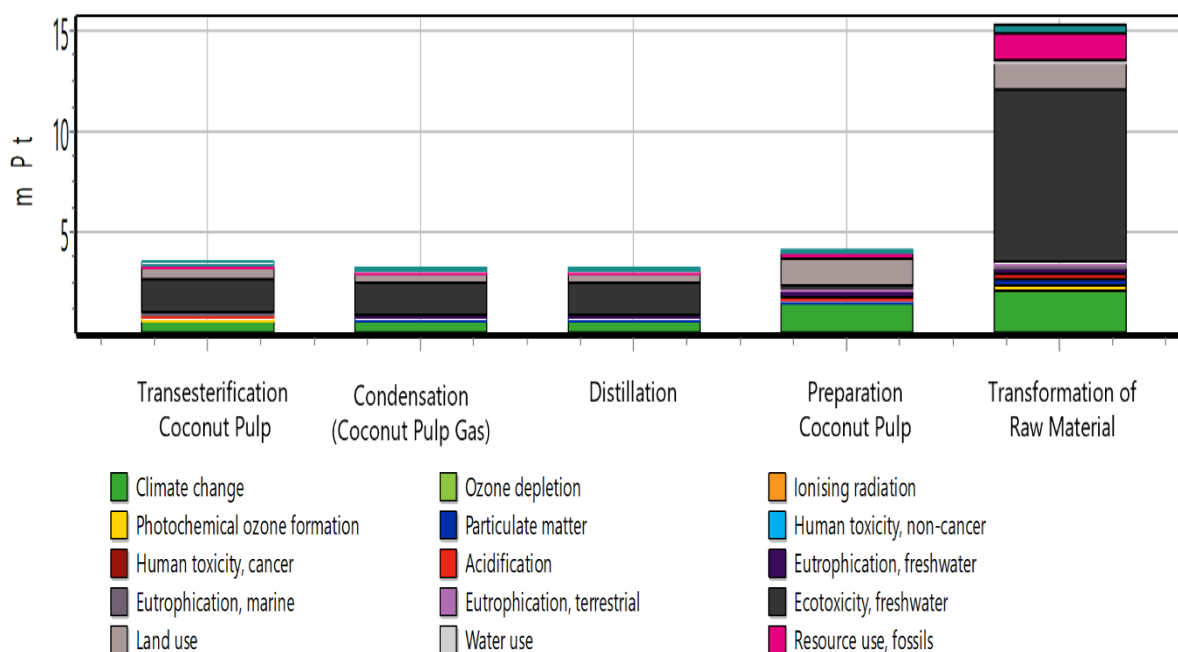


Method: EF 3.0 Method (adapted) V1.03 / EF 3.0 normalization and weighting set / Characterization
 Analyzing 1 p 'Biodiesel Overall';

Figure 4. Biodiesel Production Impact Assessment Characterization Chart

Table 4. Results of Impact Assessment Characterization on Biodiesel Production

Impact Category	Unit	Total	Trans-Esterifikasi	Condensatiom	Distilation	Preparation	Transport
Climate change	kg CO ₂ eq	204.3475	24.579644	22.4959	22.8687	56.2086	78.1945
Ozone depletion	kg CFC11 eq	1.66E-05	1.08E-06	9.81E-07	9.92E-7	8.23E-07	1.27E-05
Ionising radiation	kBq U-235 eq	11.5886	1.06794	1.003	1.04455	1.2457	7.2275
Photochemical ozone	kg NMVOC eq	0.2490	0.026379866	0.0243	0.0249	0.0401	0.1333
Particulate matter	disease inc.	3.81E-06	4.51E-07	4.12E-07	4.18E-7	5.97E-07	1.94E-06
Human toxicity	CTUh	1.98E-06	2.39E-07	2.18E-07	2.21E-7	1.96E-07	1.11E-06
Asidifikasi	mol H+ eq	0.4401	0.046217557	0.0431	0.0445	0.0865	0.2198
Eutropikasi	kg P eq	0.0497	0.00500556	0.0049	0.0053	0.0170	0.0175
Ecotoxicity	CTUe	30107.74	3823.7936	3443.356	3445.27	337.2524	19058.069
Land use	Pt	43805.86	5606.3843	5046.7323	5047.71	13964.73	14140.302
Water use	m ³ depriv.	15.9768	1.8889949	1.7458	1.7972	2.0056	8.5393
Resource use	MJ	1742.168	145.30869	136.4639	142.138	210.1204	1108.1367



Method: EF 3.0 Method (adapted) V1.03 / EF 3.0 normalization and weighting set / Single score
 Analyzing 1 p 'Biodiesel Overall';

Figure 5. Single Score Chart for Biodiesel Production

D. CONCLUSION AND SUGGESTIONS

Life Cycle Assessment (LCA) is used as an approach to evaluate the potential environmental impact on all stages of the biodiesel production life cycle. Based on the results of the analysis of biodiesel production from coconut pulp using in-situ transesterification process using microwave energy with the EF 3.0 Method (adapted) V1.03 / EF 3.0 normalization and weighting set, it is known that the transportation stage is the largest contributor to environmental impact. This stage contributes 78.19 kg CO₂-eq emissions out of a total of 204.35 kg CO₂-eq in the climate change category, and dominates energy resource use at 1108.14 MJ out of a total of 1742.17 MJ.

In addition, the preparation stage also contributes significantly to climate change with a value of 56.21 kg CO₂-eq. Thus, transportation and preparation are the stages that have the most significant impact on the environment. Therefore, optimizing logistics and increasing energy efficiency in these two stages are key steps to improving the sustainability of biodiesel production from coconut pulp.

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