

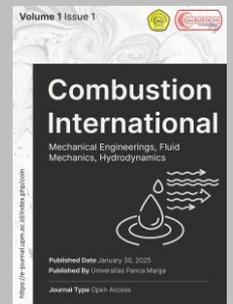
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Diversifying Biodiesel Sources in Indonesia through the Development of Non-Food Crops and the Utilization of Waste Oils

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Abstract

Indonesia's biodiesel sector has long relied on Crude Palm Oil (CPO) as the primary feedstock, but this dependency raises concerns regarding environmental sustainability and economic stability, especially due to deforestation and land-use change (LUC) emissions. This study explores alternative feedstocks for biodiesel production, including non-food oils such as *Jatropha curcas*, used cooking oil (UCO), and emerging technologies like microalgae. The paper assesses the price, yield, land availability, and environmental impacts of these feedstocks compared to CPO. The results show that UCO offers significant environmental and economic advantages, with low production costs and zero LUC emissions. *Jatropha curcas*, while still developing, has strong potential for cultivation on marginal lands and can contribute to emission reductions. Microalgae, though promising in the long term, faces technological challenges that hinder its current scalability. This research recommends a diversified feedstock strategy to reduce Indonesia's reliance on CPO, enhance energy security, and meet sustainability goals. The study calls for regulatory support, infrastructure investments, and long-term research into alternative feedstocks to create a resilient and sustainable biodiesel sector in Indonesia.

Keywords: Biodiesel production, Alternative feedstocks, Land-use change (LUC), Sustainability.

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1. Introduction

Indonesia's rapid scale-up of biodiesel, from B20 to B35 and beyond, heavily relies on crude palm oil (CPO), reflecting trends observed in other tropical biodiesel-producing countries [1]. This dependence on CPO induces competition for arable land between energy crops and food crops, exacerbating the risks associated with indirect land-use change (ILUC), which in turn raises lifecycle greenhouse gas (GHG) emissions and threatens biodiversity [1]. To address these challenges, considerable attention has shifted toward inedible-seed oils—such as *Jatropha curcas*, rubber seed, *Karanja*, and *Croton*—which are non-competing with food supplies and can be cultivated on marginal lands, offering the potential to support rural incomes while minimizing ILUC impacts [1], [2]. Concurrently, oleaginous yeasts, including *Rhodospiridium toruloides* and *Yarrowia lipolytica*, have emerged as promising microbial platforms for scalable lipid production from industrial residues, thereby mitigating land competition and enhancing feedstock supply security [3]. Collectively, integrating non-food oils and microbial feedstocks offers a viable strategy to alleviate CPO-driven environmental trade-offs, strengthen energy security, and promote more sustainable rural development in Indonesia.

Despite its high agronomic performance (~3.74 tons of oil per hectare per year), Indonesia's palm oil expansion has led to widespread deforestation, peatland degradation, and biodiversity loss, particularly in key production regions such as Sumatra and Kalimantan [4]. Life-cycle assessments reveal that emissions associated with land-use change during the plantation phase account for more than 80% of the total GHG impacts in the palm biodiesel supply chain [4], [5]. In peatland conversion scenarios, emissions reach an estimated 41.5 Mg CO₂ per hectare per year, thereby elevating the carbon intensity of palm biodiesel to up to twice that of conventional fossil diesel [6]. These findings underscore a significant conflict between Indonesia's domestic biodiesel blending mandate and its long-term climate mitigation and sustainable land-use commitments.

From an economic standpoint, crude palm oil (CPO) accounts for the largest share (42–69%) of the total biodiesel production costs in Indonesia, exposing the sector to fluctuations in CPO prices [7]. During periods of commodity price volatility, biodiesel producers become increasingly reliant on government subsidies to remain competitive with fossil diesel, which places additional pressure on fiscal resources and compromises the sector's resilience [7]. To mitigate these economic vulnerabilities, diversification into alternative feedstocks is critical. Non-edible oils—such as *Jatropha curcas* and *Croton* spp.—can be cultivated on marginal lands at lower input costs, reducing exposure to global commodity price swings [2]. Moreover, microbial lipids from oleaginous yeasts (e.g., *Yarrowia lipolytica*,

Rhodospiridium toruloides) offer a scalable, locally sourced lipid platform that decouples feedstock supply from agricultural price volatility [3]. This diversification offers both environmental benefits and enhanced economic stability.

To reduce reliance on CPO and its associated risks, Indonesia is exploring multiple alternative feedstocks. *Jatropha curcas*, which thrives on marginal, non-arable lands, avoids food crop competition and can stabilize rural incomes without inducing land-use change emissions [1]. Used Cooking Oil (UCO), derived from urban and industrial waste streams, requires no additional agricultural land, thus eliminating direct land-use change impacts while contributing to a circular economy [1]. Coconut oil, utilized in coastal regions, leverages existing smallholder systems but faces constraints due to lower per-hectare yields compared to palm oil and higher procurement costs [1]. Microalgae, as a third-generation feedstock, offer exceptionally high theoretical lipid productivities on non-arable surfaces; however, current cultivation and extraction technologies are technologically immature and cost-intensive [8]. Each alternative feedstock presents distinct trade-offs regarding cost structures, oil yields, land requirements, technological maturity, and environmental footprints, with UCO emerging as the most mature short-term solution and microalgae representing a longer-term potential, contingent on future technological advancements.

Jatropha curcas, a non-edible oilseed, can be cultivated on degraded or marginal lands, circumventing food-fuel competition while requiring minimal synthetic inputs. Life-cycle assessments of established *Jatropha* plantations indicate GHG emission reductions exceeding 85% relative to fossil diesel, primarily due to carbon sequestration and minimal land-use change impacts [9]. However, immature plantations yield lower outputs (1.5–2.5 tons of oil per hectare per year), resulting in higher establishment and harvesting costs, which limits their short-term economic viability. Conversely, microalgae exhibit remarkably high theoretical lipid productivities (>40 tons per hectare per year) on non-arable surfaces and can utilize industrial CO₂ streams. However, current photobioreactor systems and downstream processing methods demonstrate net energy deficits and global warming potential (GWP) profiles that are worse than petroleum diesel due to energy-intensive infrastructure and harvesting processes, delaying large-scale deployment until technological breakthroughs occur [10], [11].

Given these complexities, no single alternative feedstock is poised to fully replace CPO in Indonesia's biodiesel program. Instead, a diversified feedstock strategy, guided by stringent sustainability criteria, is essential to balancing energy security, environmental protection, and economic viability. This study critically assesses the potential of non-food crops and waste oils as complementary biodiesel feedstocks in Indonesia, comparing production costs, oil yields, land availability,

and life-cycle environmental performance. By synthesizing techno-economic and sustainability evidence, this research aims to inform policy pathways toward a more resilient and environmentally responsible biodiesel system that aligns with Indonesia's long-term net-zero emission targets.

2. Methods

This study aims to evaluate various alternative feedstocks for biodiesel production in Indonesia, focusing on price, yield, and land availability, with a particular emphasis on *kemiri sunan*, used cooking oil (UCO), *nyamplung*, *jatropha*, and other non-food crops. By comparing these alternatives with palm oil, the study seeks to identify the advantages and challenges of each feedstock in the context of Indonesia's evolving biodiesel policy. The research will involve a systematic review of existing studies to assess the potential of these feedstocks for biodiesel production.

2.1 Inclusion and Exclusion Criteria

The inclusion criteria for this study are limited to studies that focus on non-food or waste-based biodiesel feedstocks, provided they offer relevant data on price, productivity, production costs, and environmental impacts. The studies selected must be relevant to Indonesia or other tropical regions with similar conditions. Excluded from this review are articles that do not address biodiesel production from these feedstocks, or those that do not compare the alternatives with palm oil, or lack pertinent data on price and yield.

2.2 Study Selection Process

To gather the necessary data, a comprehensive literature search will be conducted using databases such as Google Scholar, Scopus, and PubMed. Keywords like "biodiesel alternatives," "kemiri sunan," "used cooking oil for biodiesel," "nyamplung biodiesel," and "Jatropha biodiesel" will be used to identify studies. Each article will be reviewed for its relevance and methodological rigor. For each relevant study, a summary table will be created, highlighting key data on productivity, cost, and ecological benefits of each feedstock.

2.3 Data Collection Method

In terms of data collection, price data will be gathered from national market sources and government reports, focusing on the prices of CPO (Crude Palm Oil), *kemiri sunan*, used cooking oil, *jatropha*, and *nyamplung*. Yield data will be calculated based on the amount of biodiesel produced per hectare per year for each feedstock. Additionally, data on available land for cultivation, such as *kemiri sunan* on critical land and *nyamplung* along coastal areas, will be assessed to determine the feasibility of large-scale production.

2.4 Data Analysis and Synthesis

The data analysis will involve a comparative approach, where each feedstock will be evaluated in terms of price, yield, and land availability. A comprehensive comparison table will be presented to clearly illustrate the strengths and weaknesses of each alternative. The economic feasibility of biodiesel production from each feedstock will be assessed by calculating the total production costs, which include costs for seeds, extraction, processing, and distribution. Environmental impacts, such as the reduction of CO₂ emissions and the potential for land use changes, will also be considered to evaluate the sustainability of each feedstock.

2.5 Quality Assessment and Evaluation

The quality of the studies included in the review will be assessed using established tools, such as the Cochrane Risk of Bias tool or the GRADE system, to ensure the reliability of the data. Inconsistencies across studies will be addressed, with explanations provided for any significant differences in results. The findings will be presented through tables and graphs, which will facilitate comparisons of price, yield, and land potential for each feedstock. The discussion will contextualize these findings within Indonesia's biodiesel policies, particularly with regard to the government's mandatory biodiesel targets.

2.6 Limitations of the Method

Despite its comprehensive approach, the study has some limitations. The analysis is based on existing literature, and data from local studies that have not been published may be excluded. Additionally, market conditions and inflation could cause fluctuations in price and production cost data, which will be accounted for in the analysis. Ultimately, this study will provide valuable insights into the potential for diversifying biodiesel feedstocks in Indonesia, offering a sustainable and economically viable alternative to palm oil-based biodiesel production.

3. Results and Discussion

This study provides a comprehensive analysis of alternative feedstocks for biodiesel production in Indonesia, with a focus on price, yield, and land availability. With Indonesia's ambitious biodiesel mandates, which include the implementation of B40 by January 2025 and B50 by 2026, the need for feedstock diversification is critical to reduce dependence on palm oil and mitigate competition with food crops. The study compares five main alternatives: *kemiri sunan* (*Reutealis trisperma*), *nyamplung* (*Calophyllum inophyllum*), *jatropha* (*Jatropha curcas*), used cooking oil (UCO), and *jarak pagar* (*Jatropha*).

3.1 Comparison Analysis of Feedstocks

In Indonesia's biodiesel sector, the cost of production is a critical factor, with feedstock prices constituting a significant portion of the overall production expenses

as seen in **Table 1-3**. Among the various feedstocks, Used Cooking Oil (UCO) stands out as the most cost-effective option, offering a 30-40% cost reduction compared to Crude Palm Oil (CPO), despite the additional complexity of its pre-treatment and post-treatment processes. The production costs for UCO vary depending on the treatment method: IDR 8,675 per liter for adsorption, IDR 7,214 per liter for pre-heating, and IDR 10,152 per liter for full treatment[12]. In contrast, biodiesel from CPO costs approximately IDR 12,495 per liter. This cost disparity makes UCO a viable alternative, especially if regulatory frameworks and infrastructure support its domestic use, as UCO offers a lower cost and avoids the deforestation concerns associated with CPO production.

Table 1. Biodiesel Production Costs

Feedstock	Production Cost (IDR/L)	Key Components	Ref.
Used Cooking Oil (UCO) - Full treatment	10,152	Pre-treatment complex	[12]
Palm Oil (CPO)	12,495	Feedstock: 9,349 (75%)	[12]
Used Cooking Oil (UCO) - Adsorption	8,675	Feedstock: 6,000 (69%)	[12]
Used Cooking Oil (UCO) - Pre-heating	7,214	Feedstock: 3,000 (42%)	[12]

When it comes to yield, CPO remains the highest-yielding feedstock, with a production rate of 3.74 tons per hectare per year, based on the industry standard of 20% oil extraction from Fresh Fruit Bunches (FFB) [13]. Other feedstocks, such as Jatropha, Coconut, Soybean, and Sunflower, yield significantly less oil per hectare. Specifically, Jatropha yields 0.5 to 2.5 tons per hectare per year, depending on the variety, with oil content ranging from 35% to 37%[13]. Coconut yields approximately 0.48 tons per hectare per year, which is considerably lower than CPO[14]. However, the yield of Jatropha can be enhanced through varietal improvements, and its potential for biodiesel production on marginal lands is significant, though still limited by the current yield and long-term investment requirements.

Regarding land allocation, Indonesia has a substantial amount of underutilized land, particularly for Coconut and Jatropha, which could be developed for biodiesel production. CPO dominates the biodiesel feedstock landscape, with 16 million hectares dedicated to palm oil cultivation, accounting for approximately 90% of Indonesia's biodiesel feedstock plantations. While UCO does not require dedicated land, its potential is constrained by the lack of a formal collection infrastructure, with much of the available UCO being exported. Microalgae, while promising as a future

feedstock, remains in the early stages of development, with a potential plantation area of 136,900 hectares [15], [16].

Crude Palm Oil (CPO), while offering high yields and economic advantages, presents substantial environmental challenges due to the land-use change (LUC) associated with its cultivation. The LCA for CPO shows that emissions from land-use change, particularly deforestation and peatland conversion, contribute to over 80% of the total GHG emissions in the biodiesel supply chain. Without considering LUC, CPO emissions range from 2.67 to 2.90 kg CO₂eq per liter of biodiesel. However, when LUC is included, emissions soar to 23.3-64.3 kg CO₂eq per liter when forest land is converted, and even higher when peatland is involved, at 6.08-7.09 kg CO₂eq per liter [15-16]. These emissions are significantly higher than those of traditional diesel, with peat oxidation during land conversion contributing twice the emissions of diesel. Therefore, while CPO is a high-yielding feedstock, its environmental footprint is heavily influenced by unsustainable land-use practices, making it incompatible with global sustainability goals if not sourced from certified no-deforestation plantations.

Table 2. Harvest Yield (in tons of oil per hectare per year)

Plant	Oil Yield (ton/ha/year)	Oil Content	Ref.
Palm Oil (CPO)	3.74	20% from FFB	[12]
Used Cooking Oil (UCO)	N/A (Waste)	Collected from industry	[13]
Jatropha - Common Varieties	0.5–2.0	35–37% from seeds	[13]
Jatropha - Jet-1 Agribun	1.5–2.5	35.8–37.4% from seeds	[14]
Coconut	0.48	Virgin Coconut Oil	[14]
Soybean	0.38	Soybean oil	[14]
Sunflower	0.48	Sunflower oil	[14]

In contrast, *Jatropha curcas*, a non-edible oilseed crop, offers a more sustainable alternative in terms of GHG emissions, especially in its stable production phase. During the first three years of production, *Jatropha* exhibits higher emissions (3,057.74 kg CO₂eq per ton of biodiesel) due to low productivity, but this is mitigated after the fourth year when emissions drop significantly to 380.52 kg CO₂eq per ton of biodiesel [15], [16]. This represents an 88.45% reduction in emissions compared to diesel, as *Jatropha* is typically cultivated on marginal land that does not require land-use change [17], [18]. *Jatropha*'s environmental benefits are evident in its minimal

input energy requirements and low GHG emissions during stable production phases. However, its early-stage productivity challenges and long-term investment needs limit its immediate scalability.

Table 3. Planting Area in Indonesia

Plant	Planting Area (Hectares)	% of National Plantation	Status	Ref
Palm Oil	16,000,000	~90% of biodiesel	Dominant; 60% private, 40% smallholders	[16]
Coconut	3,800,000–3,880,000	~4% potential	97% smallholder plantations; underutilized	[14]
Jatropha	~1,890	<0.1% of biodiesel	Minimal; mostly trial plantations	[13]
Sugarcane	420,100	Bioethanol, not biodiesel	Bioethanol production, not biodiesel	[14]
Used Cooking Oil	N/A	Waste stream	715 kton/year potential; mostly exported	[12]
Microalgae	136,900 (potential)	26.86% of global production	Emerging; cultivation stage varies	[17]

Used Cooking Oil (UCO), sourced from waste, offers the best environmental profile among the feedstocks analyzed, with zero land-use change (DLUC) emissions. UCO biodiesel production generates emissions in the range of 2.67 to 2.90 kg CO₂eq per liter, similar to or lower than CPO biodiesel, but without the detrimental impacts of deforestation or peatland conversion [15], [16]. UCO presents a unique advantage in that it does not compete for agricultural land or food resources and offers a waste-to-fuel solution that can help mitigate waste management issues. The lack of DLUC emissions and the use of waste as a feedstock makes UCO an environmentally superior option, although challenges in collection infrastructure and regulatory support remain. Furthermore, Indonesia has the potential to collect up to 715 kilotons of UCO per year, which could be processed into approximately 651 kilotons of biodiesel, significantly contributing to the nation’s biodiesel targets.

Microalgae, while still in the research and development stage, holds great promise for the future of biodiesel production. Microalgae cultivation does not compete for arable land and can be grown in wastewater or brackish water, offering a highly sustainable alternative. The lipid content of microalgae ranges from 20% to 50%, and it can potentially be converted into biodiesel at rates of 1.65% to 5.14% [19].

However, the low conversion rate and high costs associated with extraction methods such as solvent use and transesterification make microalgae biodiesel economically unviable at present. Microalgae's sustainability profile improves when considered within an integrated biorefinery model, where multiple products, such as bioethanol, biogas, and chemicals, are produced alongside biodiesel. This integrated approach could make microalgae biodiesel commercially viable in the long term, but it remains a long-term research priority rather than an immediate solution for biodiesel production.

CPO remains the dominant feedstock for biodiesel production in Indonesia due to its high yield, accounting for approximately 90% of the country's biodiesel feedstock. With a yield of 3.74 tons per hectare per year, CPO far surpasses alternative crops in terms of oil production potential. This high yield makes CPO economically attractive, but the environmental costs are substantial. The expansion of CPO plantations has been linked to deforestation, particularly in critical peatland areas, contributing significantly to greenhouse gas emissions. The environmental impact of land-use change (LUC), including deforestation and peat oxidation, significantly raises emissions, with values ranging from 23.3 to 64.3 kg CO₂eq per liter of biodiesel when LUC is included, compared to just 2.67-2.90 kg CO₂eq per liter when LUC is excluded. While sustainable CPO sourced from certified no-deforestation plantations (such as those with ISPO or RSPO certifications) can help mitigate these impacts, the current trend of expansion remains environmentally unsustainable. Furthermore, the increased demand for CPO could lead to further deforestation and land competition, presenting long-term sustainability risks.

Used Cooking Oil (UCO) represents a low-cost, highly sustainable alternative to CPO. UCO is a waste byproduct of the food industry, meaning it does not require additional land for cultivation and does not contribute to land-use change. Its production cost is also significantly lower—30-40% cheaper than CPO—due to its waste nature, though the pre-treatment and post-treatment processes still add complexity. UCO biodiesel is environmentally superior to CPO because it generates minimal greenhouse gas emissions (2.67-2.90 kg CO₂eq per liter) and eliminates the land-use change impact associated with CPO. Indonesia has the potential to collect up to 715 kilotons of UCO per year, which could be converted into approximately 651 kilotons of biodiesel. However, despite the environmental advantages, UCO faces significant infrastructure challenges. A nationwide collection system is not yet in place, and 98% of UCO in Indonesia is currently exported to Europe and Asia due to high market prices. To harness its full potential, Indonesia must incentivize UCO collection domestically and integrate it into national biodiesel programs like B35/B40.

Jatropha curcas is a promising non-edible oilseed crop that has gained attention for its potential as a biodiesel feedstock. It offers several advantages: it can grow on marginal and degraded lands, does not compete with food production, and has low input energy requirements. However, *Jatropha*'s performance is highly dependent on the variety and agronomic practices. The Jet-1 Agribun variety, for example, yields 1.5-2.5 tons per hectare per year, which is considerably lower than CPO but still offers potential for sustainable biodiesel production. During its early years, *Jatropha* exhibits high emissions due to low productivity (3,057.74 kg CO₂eq per ton of biodiesel), but after the third year, emissions drop significantly to 380.52 kg CO₂eq per ton of biodiesel, representing an 88.45% reduction in emissions compared to diesel. *Jatropha*'s main challenges include its low initial yield, which makes it less competitive in the short term, and its need for long-term investment in research and development, especially in breeding and pest management. Furthermore, *Jatropha* plantations currently occupy less than 2,000 hectares of land in Indonesia, far from the 2-3 million hectares needed to make a significant contribution to biodiesel production. Despite these limitations, *Jatropha* is considered a viable option for marginal land development and could play a role in rural energy independence programs, but it is not likely to replace CPO as a primary biodiesel feedstock in the short to medium term.

Coconut oil is another potential biodiesel feedstock, though it faces several challenges that limit its commercial viability. Coconut yields are relatively low, with an estimated 0.48 tons per hectare per year, which is much lower than CPO. Additionally, coconut oil is also used extensively in food and cosmetics, meaning there is a significant opportunity cost to redirecting it toward biodiesel production. While coconut oil biodiesel could be a niche solution in areas with high coconut production, it is unlikely to serve as a large-scale alternative to CPO due to its competition with the food industry and its high production costs. Virgin coconut oil is particularly expensive, with production costs around 20% higher than CPO biodiesel, making it less competitive. Therefore, while coconut oil could be considered for local biodiesel applications or co-production models (such as extracting premium oil for cosmetics and using the remaining oil for biodiesel), it is not a strong candidate for mass biodiesel production in Indonesia.

Microalgae holds great potential as a sustainable biodiesel feedstock due to its high lipid content (20-50%) and its ability to grow in non-arable land, such as wastewater or brackish water. Unlike CPO, microalgae does not compete for food crops or agricultural land, making it an attractive option for non-land-use-intensive biodiesel production. However, the commercial scalability of microalgae biodiesel remains challenging due to the high costs of cultivation and lipid extraction, as well as the low conversion rate (1.65-5.14% lipid content per hectare). The current yield

of microalgae is relatively low (0.3-0.5 tons per hectare per year), which makes it economically unviable in comparison to other feedstocks like CPO. Microalgae also faces technological hurdles, particularly in terms of the high-cost extraction methods required to convert its lipids into biodiesel. However, integrated biorefinery models—which combine biodiesel production with other bioproducts like bioethanol and biogas—could improve the economic feasibility of microalgae biodiesel in the long term. As such, microalgae is currently more of a long-term research priority than a viable feedstock for large-scale biodiesel production in Indonesia.

3.2 Challenges in Implementation

Despite the promising potential of these alternatives, several challenges remain in their large-scale implementation. *Kemiri sunan*, while highly productive, requires a long maturation period of five years before yielding its first fruit, which presents an obstacle for farmers seeking short-term returns. Moreover, the actual productivity in the field has been lower than expected, particularly in smallholder plantations, where the average yield is significantly below the potential of 15-43 tons per hectare per year. To overcome this, further research into high-yielding varieties and improved cultivation techniques is necessary.

UCO faces logistical challenges due to its uneven distribution across Indonesia and the inefficiency of current collection systems. The quality of biodiesel produced from UCO is also still under investigation, particularly in terms of long-term storage stability and technical performance. Establishing efficient collection infrastructure and setting standards for UCO biodiesel will be key to realizing its full potential.

Jatropha, once considered a promising alternative, has struggled with low productivity in the field. Despite initial expectations, the actual yield has been significantly lower, with productivity reaching only 115 kg per hectare per year, far below the expected 5-10 tons per hectare. The lack of economic incentives for farmers, coupled with the low market price of *jatropha* seeds, has contributed to the stagnation of *jatropha* development. Future efforts should focus on genetic improvements to boost yield and enhance market competitiveness.

Nyamplung has shown impressive productivity, with a seed yield of 20 tons per hectare per year, surpassing both *jatropha* and palm oil in terms of raw material yield. The oil content of *nyamplung* seeds ranges from 40% to 73%, and biodiesel yield from transesterification reaches up to 2,200 liters per hectare. However, technical challenges related to resin content in the oil need to be addressed, as resin can hinder fuel delivery. Furthermore, the presence of free fatty acids (FFA) in the oil requires additional processing to ensure fuel quality.

3.3 Strategic Recommendations

To ensure long-term sustainability and stability in Indonesia's biodiesel production, an integrated diversification strategy is essential. Relying exclusively on Crude Palm Oil (CPO) for biodiesel production has proven economically advantageous due to its high yield, but this reliance comes with substantial environmental costs, particularly deforestation and land-use change (LUC). To mitigate these risks, a diversified feedstock strategy is needed—one that incorporates a mix of CPO, Used Cooking Oil (UCO), *Jatropha* (*Jatropha curcas*), Coconut, and emerging feedstocks like microalgae. This approach will not only reduce dependence on a single feedstock but also provide a more resilient and environmentally sustainable energy source for Indonesia.

For the B40 biodiesel blending target, the proposed feedstock allocation includes 60% of the biodiesel from CPO, which amounts to approximately 11,400 KL per year. This CPO must be sourced from certified no-deforestation plantations, with methane capture technology implemented in palm oil mills to reduce emissions. The second largest allocation, 20% of the biodiesel production (about 3,800 KL per year), should come from UCO, which offers a cost-effective and environmentally superior alternative to CPO. However, to fully utilize UCO's potential, a structured collection system must be established domestically, as most of Indonesia's UCO is currently exported.

Jatropha is allocated 10% of the biodiesel production, amounting to 1,900 KL per year, and is suitable for cultivation on marginal lands. While *Jatropha* has lower yields compared to CPO, it can be a sustainable feedstock when cultivated in non-arable areas, though it requires long-term investments in breeding and agronomy to improve yield and ensure commercial viability. Additionally, Coconut is proposed for niche applications, contributing 7% to biodiesel production (1,330 KL per year), especially in regions where coconut production is abundant. However, due to its low yield and competition with food production, coconut is not a viable option for large-scale biodiesel production.

Microalgae, though still in early stages of development, offers significant long-term potential. Allocated 3% of the total biodiesel production (570 KL per year), microalgae can be grown in non-food water sources such as wastewater or brackish water. While its economic viability is currently hindered by high cultivation and extraction costs, integrated biorefinery models that produce not just biodiesel but also bioethanol, biogas, and chemicals, could make microalgae a commercially viable feedstock in the future.

For the success of this integrated diversification strategy, several regulatory measures must be implemented. First, all biodiesel must meet a carbon accounting ceiling of 2.5 kg CO₂eq/L in lifecycle emissions, including land-use change. This will

be monitored through an integrated Monitoring, Reporting, and Verification (MRV) system linked to Indonesia's National Carbon Accounting System (INCAS). Additionally, CPO must come from no-deforestation certified plantations (e.g., ISPO or RSPO), and methane capture in palm oil mills should be mandated to reduce emissions from palm oil production.

Furthermore, UCO biodiesel should be included in the B35/B40 program, with incentives comparable to CPO to promote its domestic use. A blockchain-based traceability system should also be established to ensure the transparency and sustainability of feedstocks throughout the biodiesel supply chain.

Finally, significant investment in infrastructure is required to support the collection and processing of UCO, as well as to develop *Jatropha* research and development hubs and microalgae pilot biorefinery facilities. The establishment of a nationwide UCO collection network and funding for *Jatropha* breeding programs and methane capture technologies in palm oil mills will be essential to the success of this strategy.

Based on the analysis, the following strategic recommendations are proposed:

- **Short-term Priority (1-3 years):** UCO should be prioritized for biodiesel production in the short term due to its immediate availability and low production cost. The government should establish specific regulations for UCO usage, expand collection infrastructure, and offer subsidies to incentivize UCO collection. A target of collecting 500-600 million liters of UCO per year within three years should be set.
- **Medium-term Priority (3-7 years):** *Kemiri sunan* is a promising medium-term investment due to its high yield and low production cost. A targeted production of 3 billion liters of biodiesel per year from 500,000 hectares of *kemiri sunan* should be aimed for within the next decade. This initiative could reduce the need for palm oil by 15-20 million tons per year.
- **Long-term Priority (7-15 years):** *Nyamplung* can be developed as a complementary feedstock for coastal areas, with a target of producing 1-1.5 billion liters of biodiesel annually from 500,000 hectares. Research into improving oil extraction methods and addressing resin content issues is crucial for the long-term success of *nyamplung* as a biodiesel feedstock.

3.4 Economic and Environmental Impacts

The diversification of biodiesel feedstocks in Indonesia will not only reduce reliance on palm oil but also generate significant economic and environmental benefits. The use of UCO and *kemiri sunan* alone could save up to Rp 1-2 trillion per year in production costs, reduce CO₂ emissions by 10-15 million tons annually, and create hundreds of thousands of jobs in both the agricultural and biodiesel production sectors. Additionally, the rehabilitation of critical and marginal lands

through the cultivation of *kemiri sunan* and *nyamplung* will contribute to environmental restoration and carbon sequestration.

4. Conclusion

This study underscores the need for a diversified approach to biodiesel feedstocks in Indonesia, with a focus on sustainability, energy security, and economic viability. While CPO remains the dominant feedstock due to its high yield, its environmental costs, particularly from land-use change and deforestation, pose significant challenges. UCO offers a more sustainable alternative by eliminating land-use change impacts and offering lower production costs, but it faces logistical challenges related to collection infrastructure. *Jatropha curcas*, cultivated on marginal lands, presents an environmentally friendly option with substantial GHG emission reductions, though its low yield in the early stages limits its short-term economic viability. Microalgae, with its high theoretical lipid yield, holds long-term promise but requires significant technological advancements to become commercially viable. The study concludes that a diversified feedstock strategy, combining CPO, UCO, *Jatropha*, and microalgae, is critical for ensuring Indonesia's biodiesel sector meets future energy demands while minimizing environmental impact. Regulatory frameworks, investment in infrastructure, and research into feedstock optimization are essential for achieving this balanced approach.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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