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Mangrove Fruits for Biofuel Production in Indonesia within the Framework of Climate Change Mitigation: A Literature Review of Technical and Policy Aspects

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Abstract

Aims: This study assesses the potential of mangrove fruits as a sustainable feedstock for biodiesel production to support climate change mitigation and adaptation in coastal regions.
Methods: A peer-reviewed literature published between 2008 and 2025 was conducted to evaluate oil yield, fatty acid composition, and conversion challenges associated with mangrove-based biodiesel.
Result: Quantitative findings show that several mangrove species exhibit exceptionally high oil content, notably *Cerbera manghas* Linn., with oil yields reaching 67.1%, significantly exceeding many conventional biodiesel feedstocks. Other promising species include *Suaeda salsa* (Linn.) Pall. (40%) and *Wikstroemia indica* (Linn.) (up to 39%). The extracted oils contain dominant fatty acids, palmitic, oleic, and linoleic acids, indicating strong compatibility with biodiesel standards. However, elevated free fatty acid (FFA) levels present technical constraints by reducing catalyst efficiency during transesterification, highlighting the need for pre-treatment or alternative catalytic approaches. From a policy perspective, mangrove-based biofuel development aligns with Indonesia's National Energy Policy under Presidential Regulation No. 5 of 2006, which targets 5% biofuel use by 2025.
Conclusion: Overall, mangrove fruits offer high technical potential, provided that processing, infrastructure, and policy support are strengthened.

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1. Introduction

The quest for sustainable energy sources has become increasingly urgent as the world grapples with the challenges of climate change (Erdiwansyah *et al.,* 2022). One promising area of research is the utilization of biofuels, which are derived from organic matter such as plants and algae (Nath, 2024). Among the various types of biofuels, biodiesel stands out as a viable alternative to fossil fuels due to its compatibility with existing infrastructure and its potential to significantly reduce greenhouse gas emissions. However, the production of biodiesel typically relies on crops such as soybeans, canola, and palm oil, which can compete with food crops for land and resources (Ale *et al.,* 2019). Therefore, there is a growing interest in exploring alternative feedstocks for biodiesel production that are more sustainable and less resource-intensive.

Previous studies have explored various non-food biomass sources for biodiesel production, including agricultural waste, algae, and even waste cooking oil (Atabani *et al.,* 2014; Martinez *et al.,* 2015). For instance, research on jatropha and pongamia has shown promising results in terms of oil yield and biodiesel quality (Primandari *et al.,* 2018; Sharma *et al.,* 2017). However, these crops often require significant land and water resources, which can lead to conflicts over land use and water scarcity. In contrast, mangrove forests offer a unique opportunity for sustainable biofuel production. Mangroves are coastal ecosystems that provide numerous ecological benefits, including shoreline stabilization, carbon sequestration, and habitat creation for marine biodiversity (Nyanga, 2020; Menéndez *et al.,* 2020). Moreover, mangrove fruits are rich in oil content, making them a potential feedstock for biodiesel production (Hui-Min *et al.,* 2012).

The rationale behind this study is to investigate the feasibility of using mangrove fruit as a raw material for biodiesel production (Hui-Min *et al.,* 2012; Wu *et al.*, 2008). Given the ecological importance of mangrove forests and their potential as a sustainable feedstock, this research aims to contribute to the development of biofuels that are both environmentally friendly and economically viable. By exploring the oil content in mangrove fruit and the efficiency of transesterification processes, this study seeks to identify the challenges and opportunities associated with large-scale production. This knowledge will be crucial in informing policy decisions and technological advancements necessary to support the development of mangrove-based biofuels.

The methodology employed in this study involves a comprehensive literature review. This approach will involve a thorough examination of existing research on mangrove fruit oil content, transesterification processes, and the policy frameworks necessary to support large-scale production. The literature review will include academic articles, policy documents, and technical reports to provide a comprehensive understanding of the current state of knowledge in this field. *This review uniquely integrates technical performance and policy alignment to highlight mangrove fruits as a high-oil, non-food biodiesel feedstock supporting climate change mitigation in Indonesia.*

This study aims to demonstrate that mangrove fruit can be a viable feedstock for biodiesel production through transesterification processes. The primary hypothesis is that the oil content in mangrove fruit is sufficient to support large-scale biodiesel production, and that the transesterification process can be optimized to achieve high-quality biodiesel with minimal environmental impact. Furthermore, this study posits that the use of biofuels derived from mangrove can enhance the co-benefits associated with mangrove ecosystems, including shoreline stabilization, carbon sequestration, and habitat creation for marine biodiversity.

2. Methods

The methodology of this study is based on a narrative literature review aimed at synthesizing existing knowledge on mangrove fruit oil potential, biodiesel conversion processes, and relevant policy frameworks for large-scale biofuel development. The literature review covers publications released between 2008 and 2025, reflecting the period during which mangrove-based biofuel research and national bioenergy policies have significantly evolved. Academic articles, policy documents, and technical reports were collected from reputable databases, including PubMed, ScienceDirect, and Google Scholar. The inclusion criteria focused on studies that explicitly discuss mangrove fruit oil content, fatty acid composition, transesterification or related biodiesel conversion processes, and biofuel policy frameworks. Studies that did not directly address mangrove fruits or biodiesel production were excluded. As this study does not employ a systematic literature review protocol, article selection was guided by relevance, methodological clarity, and consistency of reported data, allowing for a contextual and policy-oriented synthesis rather than a statistical meta-analysis.

Data collection is a crucial step in this methodology. Sources include academic journals and conference proceedings, government reports and policy documents, technical reports from research institutions and industry, and online databases and repositories. Search engines like Google Scholar, PubMed, and ScienceDirect will be used to gather relevant articles. Additionally, database search engines such as Web of Science and Scopus will be utilized to ensure a comprehensive search. Manual searches of relevant journals and conference proceedings will also be conducted to identify any overlooked studies.

A critical component of this study is the analysis of existing policy frameworks supporting biofuel production. This involves reviewing national and regional policies related to biofuel production. The analysis will focus on identifying incentives, regulations, and support mechanisms for mangrove planting and biofuel production. A comparison of policies across different countries will be conducted to identify best practices and areas for improvement.

Based on a peer-reviewed literature, this study develops policy and infrastructure recommendations to support the large-scale deployment of mangrove-based biofuel production. To ensure the validity of secondary data, only studies published in indexed international journals were included, with explicit reporting of geographic location, mangrove species, extraction methods, and oil yield parameters. Cross-comparison was conducted across multiple regions to account for variability in mangrove species composition and environmental conditions, which are known to influence oil quality, free fatty acid content, and conversion efficiency. By synthesizing consistent yield ranges and fatty acid profiles across diverse coastal settings, the analysis minimizes location-specific bias and enhances the robustness of technical conclusions.

The novelty of this paper lies in its integrative approach, which combines quantitative evidence on oil yield and biochemical characteristics of mangrove fruits with national bioenergy policy analysis and coastal climate adaptation perspectives. Unlike previous studies that focus on single species or laboratory-scale processes, this paper provides a cross-species, policy-relevant synthesis that positions mangrove-based biodiesel as a technically viable and strategically aligned renewable energy option for Indonesia’s coastal regions.

3. Results and Discussion

3.1 Comprehensive Overview of Mangrove Oil Content and Biodiesel Potential

Research on the oil content of mangrove fruit pulp indicates that several mangrove species contain significant levels of oil suitable for various purposes, including biodiesel production. Among the mangrove species, *Cerbera manghas* Linn., *Suaeda salsa* (Linn.) Pall., and *Wikstroemia indica* (Linn.) have shown some of the highest oil contents. For instance, *Cerbera manghas* Linn. fruit pulp has been found to contain oil yields ranging from 67.1% under normal conditions, while *Suaeda salsa* (Linn.) Pall. contains around 40% oil content, and *Wikstroemia indica* (Linn.) can reach up to 39% oil content (Hui-Min *et al.,* 2012).

Studies have demonstrated that the oils extracted from these mangrove fruits contain various beneficial fatty acids, such as palmitic acid, oleic acid, and linoleic acid, which are also found in conventional vegetable oils (Alikunhi *et al.,* 2010). These fatty acids are crucial for biodiesel production due to their high energy density and stability under various environmental conditions (Vilas Boas & Mendes, 2022). The presence of these fatty acids, particularly palmitic and oleic acids, makes mangrove oils a promising feedstock for biodiesel production.

The high Free Fatty Acid (FFA) content in mangrove oil warrants a more in-depth technical discussion, as FFAs directly influence catalyst efficiency and reaction mechanisms in biodiesel production. In alkaline homogeneous catalytic systems, such as those using NaOH or KOH, FFAs readily react with the catalyst through saponification, leading to soap formation. This process reduces biodiesel yield, increases mixture viscosity, and complicates the separation of glycerol and methyl esters, thereby lowering overall reaction efficiency and process sustainability. In contrast, heterogeneous catalysts particularly those with acidic or bifunctional properties exhibit greater tolerance to elevated FFA levels. These catalysts are capable of simultaneously promoting FFA esterification and triglyceride transesterification, making them more suitable for mangrove oils with high and variable FFA contents (Kamat *et al.,* 2013).

When compared to other vegetable oil sources like palm oil or jatropha, mangrove oils generally have lower overall oil yields (Kumar & Sharma, 2008). For example, palm oil and jatropha oil typically have higher oil yields, but mangrove oils have unique compositions that may be advantageous for specific applications. Mangrove oils contain significant amounts of free fatty acids (FFA) and triglycerides, which are crucial components for biodiesel production (Hui-Min et al., 2012). The high FFA content in mangrove oils can be beneficial as it allows for a more efficient transesterification process, which is essential for converting triglycerides into biodiesel.

The distinctive lipid profile of mangrove oils may allow for a tailored biodiesel production process that capitalizes on these unique fatty acid chains. Previous research has shown that some mangrove species contain high levels of specific fatty acids, such as *Oenothera drummondii* Herb (Spach) Walp. (71.8%), *Vitex trifolia* Linn. (69.6%), and *Rhizophora stylosa* Griff. (30%). These unique fatty acid compositions can be leveraged to optimize the biodiesel production process, potentially leading to higher yields and better fuel properties (Hui-Min *et al.,* 2012). Despite the promising potential of mangrove oils for biodiesel production, there are several challenges that need to be addressed. These include the high production cost due to the high content of free fatty acids, the toxicity of some mangrove species, and the environmental impact of large-scale cultivation. However, the advantages of using non-edible oils like those from mangroves include no competition with agricultural crops, human food, and animal feed products, as well as higher production rates and quality of biodiesel. Therefore, further research is necessary to fully exploit the potential of mangrove oils for sustainable biodiesel production.

3.2 The Potential of Biodiesel Production from Mangrove Fruits

Transesterification is a chemical reaction used to convert triglycerides in vegetable oils into methyl esters and glycerol, which ultimately produces biodiesel (Win & Trabold, 2018). The process begins with the extraction of oil from the mangrove fruit, which can be achieved using mechanical pressing or solvent extraction methods. Mechanical pressing involves physically pressing the fruits to extract the oil, while solvent extraction uses a chemical solvent to dissolve and separate the oil from the fruit pulp. Both methods aim to maximize oil yield while maintaining its natural properties.

After extraction, the oil must be purified to remove impurities and enhance its quality (Zhang *et al.,* 2018). This purification can be done through filtration, which removes solid particles, or distillation, which separates the oil from any residual solvents or other unwanted substances (Mariod *et al.,* 2017). Purification ensures that the oil is clean and suitable for the subsequent chemical reaction.

The purified oil is then subjected to the transesterification reaction, where it is mixed with methanol in the presence of a catalyst, typically sodium hydroxide ($NaOH$) or potassium hydroxide (KOH) (Daniel *et al.,* 2013). The catalyst plays a crucial role in speeding up the reaction and improving the conversion efficiency. During this stage, the reaction temperature is maintained between 50°C to 60°C to optimize the reaction rate and yield. The reaction time can vary from 30 minutes to several hours, depending on the type of catalyst used and the oil-to-methanol ratio.

Several studies have demonstrated the efficiency of converting mangrove oil into biodiesel (Hui-Min *et al.,* 2012). For instance, a study on mangrove biofuel production using multistage distillation achieved an alcohol content of 28% and an ash content of 1.91%, with the biofuel having higher viscosity and density properties compared to gasoline (Syarifudin *et al.,* 2024). Another study on the production of biodiesel from used cooking oil using Nipah fruit skin as a heterogeneous catalyst achieved a biodiesel yield of 93.3598% with a density of 860.2 g/mL and a viscosity of 2.37 mm^2/s (Ginting *et al.,* 2022). These results indicate that mangrove oil can be efficiently converted into biodiesel that meets international standards such as ASTM D6751 or EN 14214 (Sutapa & Ropa, 2019).

Despite the potential of mangrove oil as a biodiesel feedstock, several technical challenges must be addressed. One of the main issues is the high free fatty acid (FFA) content in mangrove oil, which can interfere with the transesterification reaction (Atadashi *et al.,* 2012). High levels of FFAs can lead to the formation of soap rather than biodiesel, significantly reducing the overall yield and complicating the purification process. Additionally, the use of homogeneous catalysts like sodium hydroxide (NaOH) or potassium hydroxide (KOH) poses further challenges, such as the need for a high methanol-to-oil ratio and difficulties in separating the catalyst from the final product, which can increase production costs and reduce efficiency (Ginting *et al.,* 2022).

Scalability issues also present significant obstacles to the large-scale production of biodiesel from mangrove oil (Sutapa & Ropa, 2019). The availability of raw materials is a concern, as mangroves are primarily found in specific coastal regions and may not be available in sufficient quantities to support widespread production. Additionally, the process requires substantial energy input, and the costs associated with extraction, purification, and transesterification must be optimized to make mangrove-based biodiesel economically viable. Addressing these challenges is essential to fully realizing the potential of mangrove oil as a sustainable biofuel source.

3.3 Research and Development of Biofuels in Indonesia: Policies and Strategies

The research and development of biofuels in Indonesia are influenced not only by the availability and pricing of fossil fuels but also significantly depend on government policies. Government policy plays a critical role in the success of biofuel research and development in Indonesia. Effective support is evident through collaboration among institutions involved in the development of this sector. Therefore, to enhance biofuel demand, synergy between the government and the private sector at the national, regional, and international levels is necessary, particularly in research and development efforts. This policy must address several aspects, such as basic and advanced sciences, infrastructure, economic systems, legal frameworks, and social education, all aligned with the biofuel program (Putrasari *et al.,* 2016).

One of the key policies for biofuel development in Indonesia is Presidential Regulation No. 5 of 2006, which outlines the National Energy Policy. This regulation set a target of 2% biofuel usage in national energy consumption by 2010, rising to 5% by 2025. It also mandated the Ministry of Energy and Mineral Resources to develop a blueprint for managing national energy resources, including biofuels. Furthermore, Presidential Decree No. 10 of 2006 established the National Biofuel Development Team to accelerate poverty and unemployment reduction. This decree assigned state-owned enterprises (SOEs) in the engineering sector, alongside private companies, to design and construct biofuel (green energy) plants at various production scales, aiming to increase energy productivity and efficiency (Presidential Regulation of Indonesia, 2006). Additionally, Law No. 30 of 2007 on Energy, Article 20, encourages the use of renewable energy sources, including biofuels, to reduce reliance on fossil fuels.

Despite these policies, the biofuel utilization program aimed at reducing oil-based fuel consumption in Indonesia is still far from achieving its target. The highest energy consumption, in sectors such as residential, transportation, and industry, remains dominated by fossil fuels (National Energy Council of the Republic of Indonesia, 2014). This situation is due to several factors, including contradictory policies at the central and regional levels. For instance, the Ministry of Energy and Mineral Resources (MEMR) issued Regulation No. 25 of 2013, which mandates the availability, standards, and quality of biofuels, prioritizing the use of domestically produced biofuels. However, the Ministry of Industry's policy on developing clusters for motor vehicles focuses on promoting the domestic automotive industry without considering biofuel usage. This policy contradiction could lead to an increase in vehicle numbers and higher fossil fuel consumption in the transport sector.

MEMR Regulation No. 12 of 2015 on the supply, utilization, and trading of biofuels as natural fuels outlines a phased mandate for the minimum usage of biofuels from January 2020 to January 2025. Under this regulation, the household, micro-enterprise, transportation, commercial industry, and power generation sectors are required to use fuel with a 30% biodiesel blend. For bioethanol, a 20% blend with conventional fuels is mandated in the same sectors. However, the implementation faces challenges, particularly regarding electricity supply, which is governed by MEMR Regulation No. 50 of 2017. This regulation introduces flexibility in tariffs for renewable energy projects, which could reduce production costs but also lower incentives for more expensive biofuel projects.

Law No. 30 of 2007 on Energy explicitly mandates that the utilization of New and Renewable Energy (NRE) must be enhanced by both the central and regional governments, as stipulated in Article 21. This provision positions the state as the primary actor responsible for promoting the development of renewable energy through long-term planning, regulatory support, and economic incentives. However, in practice, a policy inconsistency emerges when this legal mandate is examined alongside Presidential Regulation No. 191 of 2014 concerning the Provision, Distribution, and Retail Pricing of Fuel. This regulation restricts economic incentives, including biofuel subsidies, to specific consumer groups and designated regions. As a result, biofuel support is applied selectively rather than universally, leading to regional price disparities and constraining the competitiveness of biofuels relative to fossil fuels. This policy misalignment is further reinforced by a significant shift in the biodiesel subsidy scheme commencing in 2025. Under the revised framework, biodiesel incentives financed through the Oil Palm Plantation Fund Management Agency (Badan Pengelola Dana Perkebunan Kelapa Sawit – BPDPKS) are primarily allocated to the Public Service Obligation (PSO) segment, rather than covering the entirety of B40 biodiesel production as implemented in previous years. Consequently, biofuel producers operating outside the PSO mechanism receive limited economic support.

Such conditions undermine policy certainty for biofuel development, as the economic support normatively guaranteed under Law No. 30 of 2007 on Energy is not fully reflected in its derivative regulations. This regulatory inconsistency weakens the ability of biofuels to compete economically with fossil fuels and runs counter to the overarching objectives of renewable energy expansion and climate change mitigation embodied in Indonesia's energy law framework. The lack of a unified perspective among Indonesian policymakers in formulating biofuel utilization policies leads to contradictory regulations. Thus, a comprehensive review involving all policy stakeholders, from the President and relevant ministries to local regulations, is essential to ensure coherent and effective policies that promote biofuel utilization in Indonesia.

Presidential Decree No. 120 of 2020 sets a target to rehabilitate 600,000 hectares of mangrove forests in nine provinces from 2021 to 2024. However, progress has been inadequate, necessitating a more rational approach that balances economic and ecological interests. The "bio-rights" scheme, initially developed by Wetlands International and Alterra Green World Research, offers a sustainable solution by integrating economic incentives with environmental conservation.

The bio-rights scheme involves three main stages: First, providing microcredit to communities for developing sustainable livelihoods. Second, repayment is made not in cash but through conservation services, such as planting mangroves and using the fruits for biofuel production. Third, if conservation efforts succeed, the loan is converted into a grant, which is then redistributed among other group members. This scheme focuses on mangrove restoration and conservation through a "productive biofuel" model, integrating ecosystem functions with biofuel production. As an incentive for mangrove-based biofuel production, the bio-rights approach could be highly effective.

Microcredit provided under this scheme enables communities to develop mangrove-based biofuel enterprises, supporting economic welfare and contributing to environmental conservation. The mangroves, with their potential as a biofuel source, require protection and rehabilitation, which can be financed through microloans. The repayment is made through conservation activities like replanting mangroves, ensuring ecosystem sustainability. Successful conservation efforts can convert loans into grants, providing additional incentives for communities to continue mangrove conservation while producing biofuel. Thus, bio-rights not only promote the development of mangrove-based biofuels but also ensure ecosystem sustainability, making it a win-win solution for the environment and the local economy. The success of this scheme is measured by the survival rate of mangrove seedlings, with a rate of ≥75% converting the loan into a pure grant. The bio-rights scheme thus encourages mangrove rehabilitation as a coastal greenbelt and biofuel production (Suharti, 2017).

Mangroves can produce biofuel from their fruits, offering a strong financial incentive for local communities to protect and maintain these ecosystems. Additional income can also be generated through carbon trading, supporting environmental protection funding. Beyond biofuel production, mangroves provide other ecosystem services, such as ecotourism, which can foster entrepreneurship, enhance local skills, preserve cultural heritage, and empower communities, thereby providing further incentives for mangrove conservation. This scheme demonstrates how economic incentives can align with environmental conservation, delivering sustainable benefits to communities (Choudhary, B., Dhar, V., & Pawase, A. S., 2024).

Policies supporting mangrove conservation for community benefits are outlined in the Ministry of Environment and Forestry Regulation No. P.83/Menlhk/Setjen/Kum.1/10/2016 on Social Forestry, which involves community-managed forest management to improve welfare, social balance, and cultural dynamics. Research and development of biofuels from mangrove fruits also align with the principles of utility, advancement, and anticipation of future needs, as directed by the Ministry of Research, Technology, and Higher Education Regulation No. 44 of 2015 on Higher Education Standards for research implementation. This involves ensuring biofuels are practical and efficient with minimal environmental impact, emphasizing technological updates to enhance production efficiency, and planning for sustainability in line with energy and technology trends.

3.4 Supply Chain and Infrastructure

Biodiesel is a significant biofuel with numerous benefits across ecological, social, and economic sustainability. It is economically viable, can stabilize energy prices, and enhance welfare through expanded production. From a social responsibility perspective, biodiesel creates 18.3 million jobs per year and does not compromise food security, as it is derived from non-edible feedstock. The biodiesel supply chain is notable for its sustainability benefits to society, structured over multiple periods with four tiers: cultivation, production facilities, distribution centers, and internal and external markets. Biodiesel production from mangrove fruit involves cultivating raw materials in coastal areas, typically underdeveloped, thus fostering socio-economic development through job creation (Sims, 2003). Efficient supply chain management, encompassing all stages from mangrove cultivation to biodiesel distribution, is crucial for successful production and distribution (Diaz *et al.,* 2019).

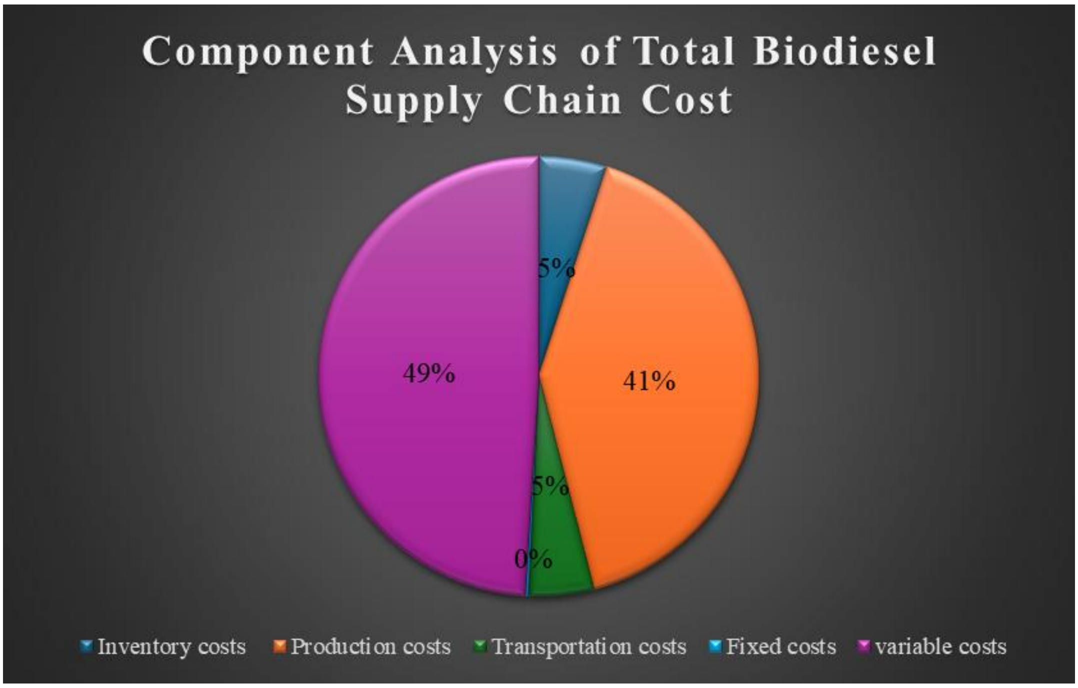

Figure 1. Component Analysis of Total Biodiesel Supply Chain Costs
Source: Mohtashami *et al.,* 2021

The biodiesel supply chain consists of several cost components: variable costs and production costs are the largest, contributing 49% and 41% respectively. Inventory costs account for only 5%, transportation costs 4.7%, and fixed costs just 0.3%. The dominance of variable and production costs highlights the importance of managing and optimizing stages directly related to production and raw material use (Figure 1). Variable and production costs cover raw material purchases, energy, and labor, which fluctuate with production volume. Inventory costs involve product storage, while transportation costs include the shipping of raw materials and finished products. Fixed costs, such as facility rent and management salaries, remain constant regardless of production volume. Efficient management of variable and production costs is crucial for minimizing total costs, while inventory and transportation control also affect supply chain effectiveness (Mohtashami *et al.,* 2021).

A non-resilient supply chain incurs an additional 20.11% in costs under disruption scenarios. However, implementing a resilience-based supply chain plan can reduce these costs by 9.46%, albeit with relatively high initial costs. Managerial insights indicate that resilience in biofuel supply chain management positively correlates with sustainability, and increased biodiesel demand can enhance social welfare and economic performance (Bahmani *et al.,* 2024). Disruptions may occur in biofuel production, given that most biomass feedstock comes from mangrove sectors vulnerable to seasonal fluctuations, climate change, and extreme weather. Inadequate transportation infrastructure in some regions can exacerbate these issues, leading to supply delays or shortages. Therefore, strategic planning is essential to maintain a consistent biomass supply year-round, contributing significantly to national energy resilience, greenhouse gas reduction, and economic development (Yazdanparast, 2022).

Biodiesel processing requires key infrastructure to ensure effective and efficient production. The primary facility for biodiesel production must be equipped for transesterification, including processing tanks, pumps, and chemical treatment units. Additional requirements include cleaning systems, cooling systems, raw material storage and processing systems, transesterification zones, monitoring and control zones, purification and cleaning zones, purification facilities, storage tanks, and a monitoring laboratory. The testing laboratory ensures biodiesel quality according to Indonesian National Standards (SNI 7182-2015) (Julianto, 2015).

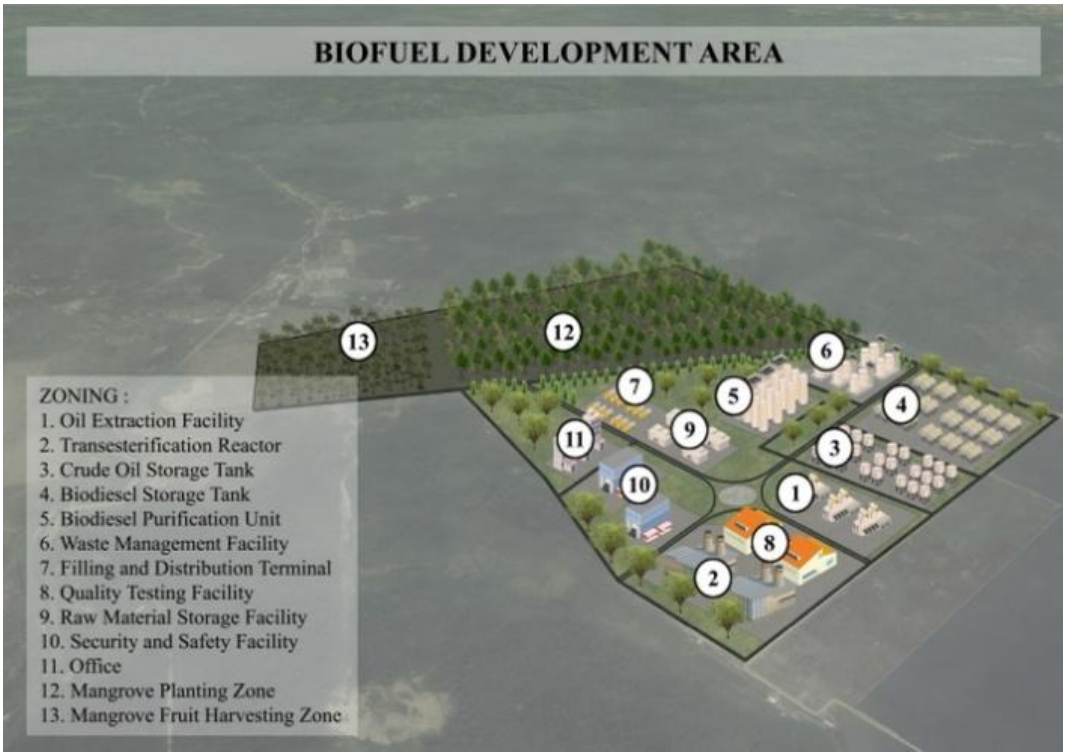

Figure 2. Biofuel Development Area
Source: Authors (2024)

Oil extraction facilities process raw materials into crude oil, which is then converted to biodiesel in a transesterification reactor. Crude oil and biodiesel storage tanks store oil before and after processing. A biodiesel purification unit ensures product quality, while a waste management facility handles production waste. Distribution terminals facilitate product delivery, and quality testing facilities maintain standards, while safety, security, and administrative offices support smooth operations (Figure 2).

3.5 Challenges in the Development of Mangrove-Based Biofuel

The development of mangrove-based biofuel faces several challenges, primarily high costs and limited scale, along with a lack of research on mangrove fruit as a biofuel feedstock. High costs are associated with extraction equipment, solvents, and catalysts, particularly at small production scales. Additionally, using specific types of mangrove fruit that are not abundant can further increase production costs. Significant energy requirements during the transesterification and purification processes also contribute to higher operational costs. The small production scale limits both production capacity and cost efficiency, making distribution and application more difficult.

Research and development on the use of mangrove fruit for biofuel production remain limited. This gap can hinder the advancement of more efficient and environmentally friendly technologies. The production of mangrove-based biofuel heavily relies on comprehensive research encompassing mangrove cultivation, fruit harvesting, biofuel production, and distribution. Variations in mangrove fruit composition among different species may lead to inconsistencies in the quality of the resulting biodiesel. Theoretical research on biofuel development involves various disciplines, including chemical engineering, biotechnology, and environmental science, intersecting with socio-economic studies (Alagumalai & Song, 2024).

To raise public awareness, educational and training programs are necessary for coastal communities on utilizing mangrove fruit for biodiesel production. Currently, there is a lack of education and awareness among communities regarding this process, which presents a barrier to developing this industry. Without adequate understanding, communities are less likely to initiate mangrove fruit management. Consequently, there is limited community participation in biodiesel production from mangrove fruit. Inadequate education can also result in technological application challenges. Without deep knowledge of the potential of mangrove fruit, innovation and technology application may be hampered.

Thus, the focus should be on increasing income, creating jobs, and contributing to environmental protection. This aligns with Indonesia's target of achieving 5% of the total energy mix from biofuels by 2025, which could positively impact employment, potentially creating around 3.4 million jobs, particularly in the agricultural sector relevant to biofuel production (Rahmadi *et al.,* 2013). Both state-owned and private companies involved in this production must provide practical training to communities on cultivating fruit-bearing mangroves, collecting mangrove fruit, oil extraction processes, and transesterification techniques. This can enhance the technical skills of communities in utilizing mangrove fruit. Following educational and technical training programs, a certification program should be established for those who meet specific standards in biodiesel processing.

To achieve the goals of Sustainable Development Goal 17 on partnerships, collaboration among research institutions, local and central governments, and the private sector is essential to form community forums with a participatory approach to enhance the success of mangrove-based biodiesel production.

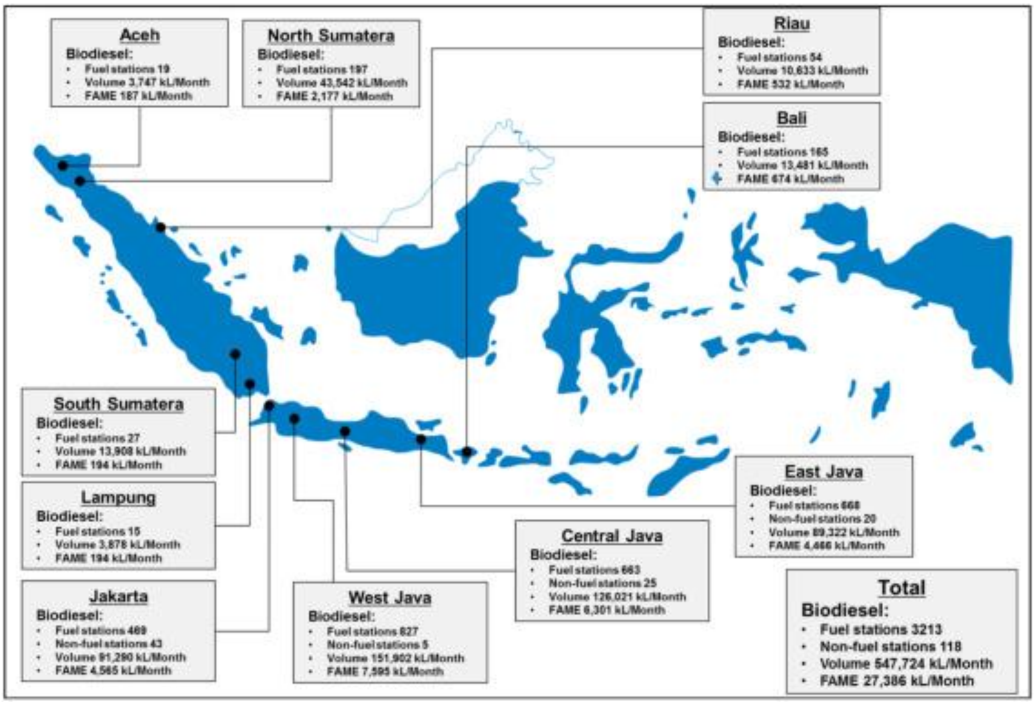

Figure 3. Biodiesel company availability in Indonesia
Source: https://www.sciencedirect.com/science/article/pii/S2352484716300300

Infrastructure limitations hinder the processing of mangrove fruit into biodiesel. As shown in Figure 3, which illustrates the availability of biodiesel plants in Indonesia, there are significant gaps. Fuel stations providing biofuels (such as up to 10% biodiesel and 5% bioethanol) are limited to certain areas. Between 2011 and 2016, only 3,213 out of 4,800 fuel stations in Indonesia supplied biofuels, primarily located in Sumatra, Java, and Bali. Additionally, 118 retailers in these areas provided biofuels. With only one oil company, Pertamina, distributing fuel, biofuel usage remains limited to 5-10% for vehicles, mainly as biodiesel (Putrasari, 2016).

Improving infrastructure from upstream to downstream is crucial for ensuring a smooth production and distribution process. Starting with the infrastructure for mangrove vegetation planting, processing plants and equipment currently lack adequate facilities to process mangrove fruit efficiently. Limited equipment and technology can reduce production capacity and biodiesel quality. Processing plants may also face issues such as unstable energy supply or raw material availability, affecting biodiesel production. Distribution networks from production to end consumers are inefficient due to inadequate storage and transportation facilities. Insufficiently distributed biodiesel refueling stations limit consumer access to biodiesel, reducing its adoption as an alternative fuel.

Optimizing policies for comprehensive infrastructure investment is essential. This includes improving road and port facilities and building targeted infrastructure for biodiesel products. One of the barriers to biofuel development is policy uncertainty. Strong policy support is needed to increase investment, which may otherwise face uncertainty regarding future investment costs and energy prices. Although biofuel investment offers promising returns, relevant policies are required to provide cost certainty. Stronger policies must consider the impact of investment cost uncertainties and biofuel market prices (Zetterholm *et al.,* 2022). Rapid investment growth can modernize processing plants with the latest technology, improving oil extraction and biodiesel production. Infrastructure improvements, coupled with increased investment, can enhance energy supply for storage infrastructure, chemical processing, and refueling stations. This would help boost the adoption of biodiesel as an environmentally friendly alternative fuel.

3.6 Multi-Stakeholder Collaboration

The development of biofuels from mangrove fruits presents a unique opportunity to combine climate change mitigation with sustainable resource utilization. However, realizing this potential requires strong collaboration among key stakeholders—government, academia, and the private sector. Effective partnerships can accelerate technological advancements, facilitate knowledge transfer, and create synergies that promote the production, distribution, and adoption of mangrove-based biofuel (Brady *et al.,* 2023).

For example, the successful development of renewable energy projects in countries such as Brazil and India highlights the importance of multi-stakeholder collaboration (Garcez & Vianna, 2009). In Brazil, the National Program for the Production and Use of Biodiesel (PNPB) brings together various sectors to enhance biodiesel production through policy incentives, research funding, and community engagement. Similarly, in India, public-private partnerships have been critical in promoting the use of bioethanol from sugarcane, involving government agencies, research institutions, and private industries to develop cost-effective technologies and infrastructure (Saravanan *et al.,* 2018).

Table 1. Multi-stakeholder collaboration potency

Collaboration Model	**Stakeholders Involved**	**Key Activities**	**Expected Outcomes**
Public-Private Partnership Consortium Fortin, E. (2013).	Government (national and local), Private companies, NGOs (Waramit *et al.,* 2023).	Biofuel optimization depends on feedstock and process conditions, while machine learning aids complex analysis but relies heavily on data quality (Alagumalai & Song, 2024).	Enhanced funding, shared risks, scalable production technology (Alagumalai & Song, 2024).
Research and Innovation Network	Universities, Research institutions,	Joint research, knowledge sharing,	Technological advancements,

	Private sector, International organizations	best practices development	innovation, global knowledge exchange.
Community-Education Partnership	Local governments, Educational institutions, Community organizations. The success of biofuel policies is determined not only by economic and agricultural conditions but also by the level of public and stakeholder support (Turcksin *et al.*, 2011).	Capacity-building programs, technical training, community awareness initiatives (OECD, 2017).	Increased community participation, sustainable resource management. Optimizing biofuel supply chains in resource-scarce regions is crucial for a sustainable energy transition (Attar *et al.* 2025).
Policy Advocacy and Implementation Forum	Policymakers, Industry representatives, NGOs, Academics (Turcksin *et al.*, 2011).	Policy development, regulatory framework creation, financial incentives, advocacy (Turcksin *et al.*, 2011).	Supportive policy environment, investment attraction, streamlined regulations (OECD, 2017).

To foster similar success in Indonesia, the following partnership models can be adopted:

- Public-Private Partnership (PPP) Consortium: A PPP consortium can bring together government bodies, private companies, and non-governmental organizations to co-invest in research, infrastructure, and technology development for mangrove-based biofuels. For instance, government agencies such as the Ministry of Energy and Mineral Resources and the Ministry of Environment and Forestry could collaborate with private sector players, such as biofuel producers and investors, to provide funding and expertise. This model would enable shared risks and benefits, encouraging innovation and scalability.
- Research and Innovation Network: A consortium of universities, research institutions, and private companies could form a research and innovation network to focus on the scientific and technological challenges of mangrove-based biofuel production. This network would facilitate joint research initiatives, knowledge sharing, and the development of best practices. In addition, such collaboration could attract international funding and expertise, leveraging global knowledge to advance local biofuel technologies.
- Community-Education Partnership: To ensure the sustainability of mangrove-based biofuel initiatives, partnerships between local governments, educational institutions, and community organizations are essential. Coastal communities need training and education on mangrove cultivation and biofuel production techniques. A community-education partnership could provide capacity-building programs, technical training, and awareness campaigns to empower communities as key players in the supply chain. This model fosters local ownership and involvement, which is crucial for the long-term success of mangrove biofuel projects.
- Policy Advocacy and Implementation Forum: Establishing a multi-stakeholder forum that includes policymakers, industry representatives, environmental NGOs, and academics could advocate for supportive policies and regulatory frameworks. This forum could develop policy recommendations, create guidelines for sustainable mangrove harvesting,

and advocate for financial incentives to attract investment. Regular dialogue within this forum would help align stakeholder interests, ensure transparency, and maintain momentum toward the shared goal of sustainable biofuel development.

4. Conclusion

This study demonstrates that mangrove fruits possess considerable potential as a sustainable biodiesel feedstock, offering synergistic benefits for climate change mitigation and adaptation. Beyond their role as an alternative energy source, mangrove-based biofuels can reinforce coastal resilience by linking energy production with mangrove conservation and rehabilitation. However, the realization of this potential is constrained not by technical feasibility alone, but by regulatory fragmentation and limited policy coherence across Indonesia's energy, forestry, and coastal governance frameworks. To address overlapping and inconsistent regulations among ministries, this study recommends the establishment of a cross-sectoral policy coordination mechanism. From a technical and economic perspective, this review identifies *Avicennia marina* and *Rhizophora mucronata* as priority species for further development. These species are widely distributed along Indonesia's coastline, exhibit relatively high fruit availability, and have been reported in the literature to possess oil characteristics suitable for biodiesel conversion.

Future research should prioritize process optimization for these selected species, particularly in improving oil extraction efficiency and transesterification performance under low-input, small-to-medium-scale production systems appropriate for coastal communities. In parallel, policy instruments such as targeted fiscal incentives, pilot-scale demonstration projects in mangrove-rich provinces, and inclusion of mangrove biofuel within Indonesia's National Energy Plan should be implemented to support market uptake and supply chain development. By aligning species selection, technological development, and regulatory harmonization, Indonesia can advance a context-specific biofuel pathway that complements, rather than competes with, mangrove conservation. Such an approach positions mangrove fruit–based biodiesel not as a mass substitute for conventional biofuels, but as a strategic, ecosystem-based energy solution that contributes to national climate goals while strengthening coastal livelihoods and resilience.

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