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Nyamplung Oil-Based Biodiesel as a Strategic Pathway for Renewable Energy Diversification in Indonesia

(*Biodiesel Berbasis Minyak Nyamplung sebagai Jalur Strategis Diversifikasi Energi Terbarukan di Indonesia***)**

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ABSTRACT

Indonesia's continued dependence on fossil fuels has intensified the need for renewable energy sources that are technically feasible, environmentally sustainable, and derived from locally available biological resources. Nyamplung oil (Calophyllum inophyllum) represents a promising non-edible feedstock for biodiesel production because of its high seed oil content, ranging from 40% to 74%, and its limited competition with food supply chains. This review critically evaluates the potential, conversion pathways, catalyst systems, and fuel-quality characteristics of biodiesel derived from nyamplung oil. The conversion process generally involves esterification pretreatment followed by transesterification, particularly because crude nyamplung oil contains high free fatty acid levels that may reduce conversion efficiency when alkaline catalysts are used directly. The reviewed studies indicate that biodiesel yield is strongly influenced by catalyst type, methanol-to-oil molar ratio, reaction temperature, and reaction time. Heterogeneous catalysts, particularly those derived from natural or waste-based materials, show considerable potential due to their reusability, reduced wastewater generation, and improved environmental performance. Optimized production systems have achieved biodiesel yields of up to 98.15%. The resulting biodiesel generally complies with national and international standards, including SNI 7182:2015, ASTM D6751, and EN 14214, based on viscosity, density, cetane number, acid value, and flash point. Overall, nyamplung oil-based biodiesel offers a strategic pathway for renewable energy diversification in Indonesia while supporting sustainable resource utilization and reducing dependence on fossil fuels.

KEYWORDS*: *biodiesel; Calophyllum inophyllum; heterogeneous catalyst; nyamplung oil; renewable energy

INTISARI

Ketergantungan Indonesia pada bahan bakar fosil yang bersifat terbatas dan tidak terbarukan masih menjadi permasalahan utama, sehingga diperlukan upaya pengembangan energi alternatif yang memanfaatkan sumber daya lokal secara berkelanjutan. Salah satu potensi yang menjanjikan adalah minyak nyamplung (*C. inophyllum*) yang memiliki kandungan minyak tinggi, yaitu sekitar 40–74% dari berat biji, serta tidak termasuk bahan pangan sehingga tidak bersaing dengan

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kebutuhan konsumsi manusia. Penelitian ini bertujuan untuk mengkaji potensi, proses produksi, serta kualitas biodiesel dari minyak nyamplung sebagai salah satu solusi energi terbarukan di Indonesia. Metode pembuatan biodiesel dari minyak nyamplung melalui dua tahap utama, yaitu esterifikasi dan transesterifikasi, dengan penggunaan katalis homogen maupun heterogen. Proses ini dipengaruhi oleh beberapa parameter operasi seperti suhu reaksi, rasio molar metanol: minyak, waktu reaksi, serta jenis katalis yang digunakan untuk memperoleh hasil yang optimal. Hasil kajian menunjukkan bahwa optimasi kondisi proses dapat menghasilkan rendemen biodiesel hingga 98,15%. Biodiesel yang dihasilkan juga memenuhi standar nasional dan internasional berdasarkan parameter mutu seperti viskositas, densitas, angka setana, angka asam, serta memiliki keunggulan berupa titik nyala yang tinggi sehingga lebih aman dalam penyimpanan dan penggunaan. Dengan demikian, biodiesel dari minyak nyamplung berpotensi besar sebagai sumber energi alternatif yang dapat mendukung diversifikasi energi nasional, sehingga mengurangi ketergantungan terhadap bahan bakar berbasis fosil, serta mendorong pemanfaatan sumber daya lokal secara berkelanjutan di Indonesia.

KATA KUNCI: Biodiesel; energi terbarukan; minyak nyamplung; transesterifikasi

INTRODUCTION

The global energy crisis and increasing concerns regarding the environmental consequences of fossil fuel utilization have intensified the search for sustainable alternative energy sources. Renewable energy is increasingly recognized as a central component of future energy systems and has become a major global priority in response to climate change, energy insecurity, and fossil fuel depletion. As an archipelagic country with high biodiversity, Indonesia has great potential in developing renewable energy, especially biodiesel from vegetable oil-based feedstock. (Pambudi *et al*., 2023; Yana *et al*., 2022). To date, the vegetable oil-based feedstock commonly used for biodiesel in Indonesia is palm oil. (Chana *et al*., 2025). However, dependence on palm oil as raw material raises various challenges such as sustainability issues, land conflicts and impact on food prices. (Meijaard *et al*., 2020; Huda & Dhenada, 2024). Hence, the development and use of non-food-based feedstocks are essential to avoid competition with food crops. One example of a plant-based raw material that does not compete with food crops is nyamplung.

The seeds of *C. inophyllum* can be utilized as a raw material for biodiesel production. This is due to the non-edible nature of the seeds (Ilham & Mansor, 2020). This plant does not compete with food-based supply chains and has a high oil content. Nyamplung oil yields reach 40-73%, superior to other raw materials such as palm oil and jatropha curcas. (Muderawan & Daiwataningsih, 2016; Musta *et al*., 2017). In addition, nyamplung oil has superior characteristics, such as exhibiting higher

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energy efficiency and greater combustion stability than kerosene and more environmentally friendly emissions. (Lestari *et al.*, 2024). However, despite extensive literature on various aspects of nyamplung-based biodiesel production, existing studies remain fragmented and predominantly limited to individual parameters, including catalyst selection, reaction optimization, and fuel property evaluation.

The process of converting *C. inophyllum* oil into biodiesel involves technical stages such as esterification and transesterification (Juwono *et al.*, 2017). The findings indicate that biodiesel produced from nyamplung oil met the specifications outlined in the Indonesian National Standard (SNI) in terms of viscosity, density, and cetane number (Adenuga *et al.*, 2021). Moreover, the use a hierarchical active carbon-based catalyst impregnated with Pd metal resulted in a biodiesel conversion product of 72.18% (Trisunaryati *et al.*, 2021).

The conversion of *C. inophyllum* oil into biodiesel is in line with governmental strategies to expand the utilization of renewable and environmentally friendly fuel resources. *C. inophyllum*-based biodiesel can be a strategic solution to support national renewable energy targets while reducing dependence on fossil fuels Hence, this review provides a critical synthesis of the literature on the biodiesel potential of *C. inophyllum* oil, with special attention to feedstock characteristics, conversion routes, optimization strategies, and fuel quality indicators. Furthermore, this study seeks to identify prevailing research gaps and provide scientific insights that may contribute to the advancement of sustainable biodiesel technologies and support renewable energy diversification strategies in Indonesia and other tropical regions.

RESEARCH METHODS

Review Scope

This study was designed as a literature-based review focusing on the production and quality of biodiesel derived from *Calophyllum inophyllum* oil. The review covers scientific studies conducted in regions where nyamplung has been investigated as a biodiesel feedstock. Rather than being limited to a specific experimental site, the scope of this review is defined by published literature addressing feedstock characteristics, biodiesel production processes, catalyst applications, and fuel-quality assessments related to nyamplung oil.

Data Collection Techniques

Data collection was carried out via a systematic review of scientific articles and conference proceedings. A comprehensive literature search was carried out across key scientific databases, namely Scopus, Web of Science, ScienceDirect, SpringerLink, Google Scholar, and SINTA. The search process used combinations of keywords such as "*Calophyllum inophyllum*," "nyamplung oil," "biodiesel production," "transesterification," "esterification," "renewable energy," "heterogeneous

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catalyst," "homogeneous catalyst," and "biodiesel quality." Boolean operators (AND, OR) were used to refine the search and increase the relevance of the publications found.

Inclusion criteria consisted of: (1) studies examining the conversion of *C. inophyllum* oil into biodiesel; (2) publications reporting biodiesel yield, process parameters, catalyst performance, or fuel quality characteristics; (3) articles published in peer-reviewed journals; and (4) publications available in English. Conversely, studies lacking adequate methodological information, duplicate publications, and literature unrelated to biodiesel production were excluded from this review.

Research Procedures

The review was conducted through four stages: (1) literature identification, (2) literature screening and selection, (3) data extraction, and (4) data synthesis.

Data Analysis

A qualitative-descriptive and comparative analysis approach was employed to synthesize the collected literature. The analysis focused on identifying relationships between production variables and biodiesel performance indicators reported in previous studies. Moreover, a comparative analysis was performed to assess how different catalyst types, reaction temperatures, methanol:oil molar ratios, and reaction durations affect biodiesel yield and quality. Trends, consistencies, and discrepancies among the reviewed studies were critically examined to identify knowledge gaps and opportunities for future research. To enhance the scientific rigor of the review, findings from multiple studies were cross-compared and interpreted within the broader context of renewable energy development and sustainable biodiesel production. This approach enabled the formulation of evidence-based conclusions regarding the feasibility and prospects of nyamplung oil as a biodiesel feedstock.

RESULTS AND DISCUSSION

The Potential of Nyamplung Oil as a Biodiesel Raw Material

Calophyllum inophyllum is a plant endemic to several regions in Indonesia. Besides Indonesia, *C. inophyllum* is also found in other countries such as India, Malaysia, Australia, and Nigeria. (Arumugan & Ponnusami, 2019a). Nyamplung oil (*C. inophyllum*) is a potential feedstock for biodiesel development in Indonesia.

Table 1. Taxonomic Classification of Nyamplung (*C. inophyllum*)

Kingdom	Plantae
Subkingdom	Tracheobionta (Vascular plants)
Superdivision	Spermatophyta (Seed plants)
Division	Magnoliopsida (Dicotyledon)
Class	Dilleniidae
Subclass	Theales
Order	Calophyllaceae
Family	*Calophyllum* L.
Genus	*Calophyllum inophyllum*
Species	

Source : Arumugam & Ponnusami (2019a)

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Nyamplung seeds contain a substantial amount of oil, representing about 40–74% of their weight. The principal fatty acids in the oil include oleic acid (40–50%), linoleic acid (20–35%), palmitic acid (12–16%), and stearic acid (10–12%) (Muderawan & Daiwataningsih 2016; Prasannakumar *et al*. 2022). These fatty acids are predominantly unsaturated and play an essential role in biodiesel production. Nevertheless, nyamplung oil exhibits a high fatty acid content of 98.19%, which necessitates an esterification process to lower the concentration of free fatty acids (FFA) (Azhar *et al*., 2024; Hasibuan *et al*., 2013). Furthermore, nyamplung oil exhibits an acid value of 36.50 mg KOH/g, a peroxide value of 5.57 Meq/kg, an iodine value of 93.92 g I_2/100 g, a density of 0.876 g/cm^3, and is characterized by a dark green color (Prasannakumar *et al*., 2022).

The Process of Converting Nyamplung Oil into Biodiesel

The synthesis of biodiesel from nyamplung oil is mainly carried out via a transesterification reaction process. This process involves a reaction between triglycerides contained in the oil and alcohol, commonly methanol, in the presence of catalytic agents such as alkaline, acidic, or enzymatic catalysts. Through this reaction, triglycerides are transformed into fatty acid methyl esters (FAME) as the primary product, with glycerol produced simultaneously as a by-product (Singh *et al*., 2025; Saputra *et al*., 2022). Nevertheless, the elevated free fatty acid content in crude nyamplung oil remains a major limitation in biodiesel production. High concentrations of free fatty acids can induce saponification reactions when base catalysts are employed during the transesterification process. Consequently, this phenomenon may reduce biodiesel yield and negatively affect overall process efficiency (Azhar *et al*., 2024). Hence, esterification pretreatment using an acid catalyst is required. The selection of catalyst, together with key operating parameters such as reaction temperature, reaction time, and oil:alcohol molar ratio, significantly influences both the yield and quality of biodiesel produced, as presented in **Table 2**.

Table 2 shows that the catalysts employed in the conversion of nyamplung oil into biodiesel are classified into homogeneous and heterogeneous types. Homogeneous catalysts are catalysts that are present within the same phase as the reactants involved in the reaction system. Typical homogeneous catalysts applied in the transesterification of nyamplung oil include CH_3COONa, NaOH, and KOH (Dewang *et* al., 2017; Qadariyah *et al*., 2018; Singh *et al*., 2025). This process, however, leads to the formation of liquid waste from catalyst residue washing and demands higher energy consumption for subsequent product separation (Fadhillah & Sari, 2023). As a result, the utilization of homogeneous catalysts is associated with environmental drawbacks, including pollutant emissions and elevated recycling costs. Notably, experimental findings demonstrate that homogeneous catalysts are capable of yielding up to 96% biodiesel (FAME) conversion under microwave-assisted conditions, employing 1% KOH as the catalytic agent. (Qadariyah *et al*., 2018).

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Table 2. Comparison of Biodiesel Production from Nyamplung Oil (*C. inophyllum*) via Transesterification

Catalyst	Molar ratio of methanol : oil	Reaction time (min)	Temperature (°C)	Biodiesel Yield (%)	References
KOH 1% (*Batch method*)	6:1	15	65	92.3	Singh *et al*., 2025
KOH 1% (*Continuous method*)	8:1	20	65	92.3	Singh *et al*., 2025
Geopolymer Activated with 3% NH_4NO_3	12:1	120	65	95.14	Utama *et al*., 2024
Ksil-Geo 2%	12:1	120	65	97	Saputra *et al*., 2022
NaSil-Geo 2%	12:1	120	65	88	Saputra *et al*., 2022
CaO 4%	16:1	60	60	54	Febriana *et al*., 2022
KOH 0.8%(SUNWTH Biodiesel)	2:3	150	60	87.08	Adenuga *et al*., 2021
KOH 0.8%(75WTH Biodiesel)	2:3	150	60	95.76	Adenuga *et al*., 2021
Zn-doped CaO 5%	9.66:1	81.31	56.71	91.95	Rajendiran *et al*., 2020
GO/metal composite 8%	10:1	180	65	95.37	Marso *et al*., 2017
Residual ash from sugarcane leaves 5%	19:1	180	64	97	Arumugan *et al*., 2020b
KOH 1%	9:1	60	Heating method	96	Qadariyah *et al*., 2018
CH_3COONa 1%	9:1	60	Heating method	87	Qadariyah *et al*., 2018
KOH 1%	6:1	90	55-60	86.15	Dinesh *et al*., 2016
KOH 2%	6:1	0.43*	65	65.96	Kurniati *et al*., 2019
$BMIMHSO_4$: NaOH 1%	9:1	6	60	92.81	Handayani *et al*., 2017
NaOH 1%	6:1	120	55	95.86	Dewang *et al*., 2017
Al-MCM-41	1:3	60	60	98.15	Juwono *et al*., 2017
Ash derived from seashells ($CaCO_3$) 3%	8:1	180	60	87.4	Zuhra *et al*., 2015

*Using induction electromagnetic method

In heterogeneous catalytic systems, the catalyst is physically separated from the reactants by residing in a different phase. Heterogeneous catalysts are generally in the solid phase (Mirzayanti *et al*., 2022). Heterogeneous catalysts offer a sustainable alternative in the transesterification process. The application of heterogeneous catalysts provides several benefits, such as efficient post-reaction separation, catalyst regeneration and reuse, flexibility in material selection, and the valorization of natural and waste-derived materials (Mirzayanti *et* al., 2016; Zítová *et al*., 2025). The heterogeneous catalyst (Table 2) with the highest biodiesel conversion yield (FAME) was the 5% sugarcane leaf ash residue catalyst with six repetitions. The resulting methyl ester yield reached 85%. (Arumugan *et al*., 2020b). Material diversification aims to utilize various usable materials. As shown in Table 2, heterogeneous catalysts such as CaO, graphene oxide, MCM-41, palm oil mill bottom ash, seashell ash, and ash residue from sugarcane leaves have been employed. Among them, the highest biodiesel yield was obtained using MCM-41 impregnated with sodium aluminate, reaching 98.15% (Zuhra *et al*., 2015; Marso *et al*., 2017; Juwono *et al*., 2017; Arumugan *et al*., 2020b; Saputra *et al*., 2022). Furthermore, heterogeneous catalysts can be developed by utilizing natural materials or waste. Examples of natural and waste-based materials presented in Table 2 include CaO derived from limestone in Madura, palm oil mill bottom ash, seashell ash, and ash residue from sugarcane leaves. The methyl ester yields obtained from these three heterogeneous catalysts sourced from natural and waste materials were relatively high. This indicates that catalysts derived from natural resources can also be effectively used to assist in converting *C. inophyllum* oil into biodiesel. (Arumugan *et al*., 2020b; Saputra *et al*., 2022; Febriana *et al*., 2022).

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Moreover, catalyst composition appears to play a more decisive role than merely increasing the methanol:oil molar ratio. For instance, although residual ash from sugarcane leaves and geopolymer-based catalysts were applied at relatively high methanol ratios (12:1–19:1), the resulting biodiesel yields were comparable to those obtained using conventional alkaline catalysts at lower molar ratios. This finding indicates that excessive methanol addition does not necessarily guarantee higher biodiesel production and should be evaluated in conjunction with catalyst performance (Febriana *et al*., 2022).

Most transesterification processes were performed at temperatures between 55 and 65°C, reflecting the boiling point range of methanol and providing optimal conditions for achieving efficient conversion while minimizing energy expenditure. However, prolonged reaction times did not always result in improved biodiesel yields. Several studies achieved yields above 90% within 15–90 minutes, whereas longer reaction durations of up to 180 minutes produced only marginal improvements. Consequently, optimization of reaction time is essential to maximize process efficiency while reducing operational costs (Singh *et al*., 2025; Juwono *et al.,* 2017).

Table 3 shows a comparison demonstrating that both catalyst systems are capable of producing high biodiesel yields. However, there are significant differences in process economics and environmental sustainability.

Table 3. Comparative Analysis of Homogeneous and Heterogeneous Catalyst Performance in the Transesterification of *C. inophyllum* Oil for Biodiesel Production

Parameter	Homogeneous catalyst	Heterogeneous Catalyst
Maximum biodiesel yield	95.86%	98.15%
Production cost	High due to catalyst separation and purification requirements	Low due to the catalyst can be recycled
Environmental impact	High wastewater generation from washing and neutralization processes	Lower environmental impact due to catalyst reusability and reduced wastewater generation.

Sources : Dewang et al. (2017); Juwono et al. (2017); Alisha et al. (2022); Chana et al. (2025)

Evaluation of biodiesel conversion efficiency revealed that heterogeneous catalysts outperformed homogeneous catalysts, achieving a maximum yield of 98.15% compared with 95.86%, respectively The results highlight that catalyst modification and the engineering of heterogeneous catalyst materials can promote the generation of active surface sites, thereby facilitating more efficient conversion processes (Alisha *et al*., 2022a). Furthermore, several studies have reported that heterogeneous catalysts offer better catalytic stability and can maintain performance over multiple reaction cycles, thus enhancing their practical application in large-scale biodiesel production (Alisha *et al*., 2022b).

In addition to conversion efficiency, catalyst selection significantly impacts production costs. Due to their high reactivity and simple reaction pathways, KOH and NaOH remain the most prevalent homogeneous catalysts. Nevertheless, this approach introduces operational challenges, as it demands extensive post-reaction separation and washing stages (Naseef & Tulaimat, 2025). In contrast, heterogeneous catalysts can be readily recovered from the reaction mixture and reused in

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subsequent production cycles, thereby reducing catalyst consumption and overall production costs (Alisha *et al*., 2022b).

Transesterification processes using homogeneous catalysts generally produce large amounts of wastewater due to repeated washing and purification steps. Consequently, environmental pollution, as wastewater treatment and chemical disposal pose significant challenges (Hosseinzadeh-Bandbafha *et al*., 2022). In contrast, the reusability of heterogeneous catalysts reduces wastewater generation and minimizes secondary pollution, thereby promoting a more environmentally sustainable biodiesel production process (Amenaghawon *et al*., 2026).

Recent advancements can be achieved through the use of heterogeneous catalysts derived from natural resources and waste-based materials, which are capable of improving reaction selectivity. Such catalyst modifications may improve surface area and thermal stability, thereby increasing the yield of methyl esters (biodiesel products). The development of natural and waste-based catalyst materials thus represents a sustainable solution for the biodiesel industry in Indonesia.

Biodiesel Quality from Nyamplung Oil

Biodiesel produced from *C. inophyllum* oil generally meets several quality standard parameters of biodiesel as specified in the Indonesian National Standard (SNI 7182:2015) and international standards (ASTM D6751, EN 14214), such as viscosity, cetane number, acid value, density, and flash point. According to national (SNI 7182:2015) and international standards (ASTM D6751, EN 14214), biodiesel viscosity should range between 2.3–6 mm^2/s. Previous studies have reported viscosity values of 2.93, 3.45, 4.54, and 5.54 mm^2/s. Therefore, the viscosity of biodiesel derived from *C. inophyllum* oil complies with SNI 7182:2015, ASTM D6751, and EN 14214 standards (Utama *et al*., 2024; Aneeque *et al*., 2021; Kurniati *et al*., 2019). Furthermore, the density of biodiesel according to the quality standards of SNI (7182:2015) and ASTM D6751 is 850–890 kg/m^3, while according to the international standard EN 14214 it is 860–900 kg/m^3 (Kurniati *et al*., 2019; Adenuga *et al*., 2021). The density values of *C. inophyllum* biodiesel reported in previous studies vary between 872 and 892 kg/m^3, specifically 872, 882.3, and 892 kg/m^3. (Christina *et al*., 2013; Adenuga *et al*., 2021; Utama *et al*., 2024). This indicates that *C. inophyllum* biodiesel complies with both national and international biodiesel quality standards. The presence of long carbon chains and a high content of saturated fatty acids in *C. inophyllum* oil contributes to improved viscosity stability (Senthilkumar *et al*., 2022).

As an indicator of diesel fuel combustion quality, the cetane number of *C. inophyllum* biodiesel has been reported to vary between 54.2 and 61.1 (Christina *et al*., 2013; Adenuga *et al*., 2021; Saputra *et al*., 2022). According to the national quality standard SNI 7182:2015 and the international standard EN 14214, the minimum cetane number for biodiesel is 51, while the international ASTM D6751 standard requires a minimum of 47 (Adenuga *et al*., 2021; Saputra *et al*., 2022). Thus, it can be observed that *Calophyllum inophyllum* biodiesel has a cetane number exceeding both national and

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international standard limits. This indicates that *C. inophyllum* biodiesel demonstrates improved ignition quality and combustion efficiency, reduced emissions and improved combustion characteristics (Christina *et al*., 2013).

The esterification process catalyzed by sulfuric acid or hydrochloric acid is conducted to reduce the free fatty acid content, thereby lowering the acid value. The acid value is an important parameter that indicates the free fatty acid (FFA) content in biodiesel. Based on national biodiesel quality standards (SNI 7182:2015) and international standards (ASTM D6751, EN 14214), the maximum allowable acid value is 0.5 mg KOH/g (Kurniati *et al*., 2018). A reduced acid value ensures that biodiesel is chemically stable and does not cause corrosion in the fuel system. Several studies have shown that the acid value of nyamplung biodiesel ranges from 0.36 to 0.46 mg KOH/g (Sarwono *et al*., 2017; Saputra *et al*., 2022; Utama *et al*., 2024). This shows that nyamplung biodiesel has an acid number that meets national and international standards.

The flash point is defined as the lowest temperature at which a fuel produces enough vapor to form an ignitable mixture in the presence of an ignition source. This parameter is important for determining the safety of biodiesel storage and transportation (Zikri *et al*., 2025). The flash point is strongly influenced by the composition of long-chain methyl esters (C18–C20) present in biodiesel synthesized from *C. inophyllum* oil. The predominance of these compounds contributes to higher flash point values owing to their lower volatility relative to petroleum-based fuels. (de Mattos *et al*., 2015). The flash point standard for biodiesel according to SNI 7182:2015 is a minimum of 100°C, while the international standards ASTM D6751 and EN 14214 require minimum values of 93°C and 120°C, respectively. The flash point of *C. inophyllum* biodiesel has been reported in various studies to range from 134 to 172°C (Dinesh *et* al., 2016; Adenuga *et al*., 2021; Saputra *et al*., 2022; Utama *et al*., 2024). These studies show that nyamplung biodiesel has a flash point that meets national and international standards

CONCLUSION

This review demonstrates that *Calophyllum inophyllum* oil has significant potential as a sustainable, non-edible feedstock for biodiesel production in Indonesia. Its high oil content, broad availability, and limited competition with food resources make it a promising alternative to conventional biodiesel feedstocks. However, the successful conversion of nyamplung oil into biodiesel depends on effective pretreatment, optimized reaction conditions, and appropriate catalyst selection, particularly because of its relatively high free fatty acid content. The reviewed literature indicates that heterogeneous catalysts, especially those derived from natural and waste-based materials, offer important advantages in terms of reusability, reduced wastewater generation, and improved environmental performance. Biodiesel produced from nyamplung oil generally meets national and international quality standards, indicating its technical feasibility as a renewable diesel

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substitute. Therefore, further research should prioritize feedstock pretreatment, catalyst durability, lifecycle assessment, and scale-up strategies to strengthen the role of nyamplung biodiesel in Indonesia's renewable energy transition.

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