Review Article

The Treasure of Palm Oil as an Invaluable Renewable Energy Source

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Abstract

Escalating global demand for environmentally friendly power has driven the search for fossil-fuel replacements derived from plant sources. Among renewable options, CPO distinguishes itself thanks to its large-scale presence and easy accessibility, high production capacity, and efficient conversion to biodiesel. This paper examines how technological advancements and sustainability measures enhance CPO's viability as an alternative energy source. Employing a qualitative research approach, this study adopts a Systematic Literature Review (SLR) method using the PRISMA protocol to ensure transparency and replicability in the selection and analysis of the literature. Data collection was conducted via the ScienceDirect database using the keyword "heterogeneous catalyzed transesterification of crude palm oil for biodiesel," yielding 1,804 results. After refining the search based on thematic relevance, publication year (2022–2025), article type (research articles), and open-access criteria, a total of 34 articles were deemed eligible for in-depth analysis. Thematic analysis was applied to synthesize findings on technological progress and sustainability. The results reveal that adopting heterogeneous catalysts, utilizing CPO by-products such as PFAD, and integrating CPO-based biodiesel into hybrid systems yield notable gains in both energy efficiency and sustainable outcomes. The study concludes that CPO holds substantial promise as a reliable renewable energy source, provided it is supported by continuous technological innovation and strong policy frameworks. Future research should focus on socio-economic implications and cross-regional comparative assessments.

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Introduction

Mounting environmental concerns, particularly about climate change, are driving a major overhaul of the global energy landscape, resource depletion, and the volatility of fossil fuel markets. While still responsible for supplying about 80% of global primary energy, fossil fuels are increasingly challenged by their environmental impacts, particularly their links to GHG emissions and climate change [1]. In response, nations worldwide have intensified their pursuit of cleaner, more sustainable, and less geopolitically vulnerable renewable energy sources. The shift towards alternative fuels is not merely a technical necessity but also a geopolitical and environmental imperative [2].

Among renewable energy sources, biofuels have attracted significant attention for their potential to replace conventional diesel and gasoline without requiring substantial changes to existing engine infrastructure. First-generation biofuels, including ethanol and biodiesel, are derived from crop-based resources such as corn, sugarcane, soybeans, and palm oil [3]. While newer generations of biofuels, such as those derived from algae and lignocellulosic sources, are advancing steadily, first-generation biofuels still dominate the market due to their established scalability and economic appeal [4].

The use of crude palm oil (CPO) in biodiesel synthesis has gained traction due to its exceptional productivity and cost-effectiveness. With average oil yields of 4,000–6,000 liters per hectare annually, palm oil significantly outperforms other oilseed crops such as soybean (446 L/ha), sunflower (952 L/ha), and rapeseed (1,190 L/ha) in terms of land-use efficiency [5]. Its status as a leading biodiesel feedstock is further reinforced by its dominance in global vegetable oil production, with Indonesia and Malaysia alone accounting for over 85% of the world's palm oil exports [6].

The strategic relevance of palm oil extends beyond its yield. In Southeast Asia, palm oil is not only an economic cornerstone but also a potential catalyst for rural development and energy security. Countries like Indonesia and Malaysia have instituted mandatory biodiesel blending policies (e.g., B30 and B20 programs) to reduce their reliance on imported petroleum products and stabilize domestic fuel markets [7]. Moreover, palm oil biodiesel has been shown to reduce lifecycle GHG emissions by up to 65% when derived from sustainably sourced palm oil and processed with optimized catalytic systems [8].

The role of palm oil in renewable energy remains controversial, as critics point to allegedly environmental drawbacks, including deforestation, species loss, and emissions from disturbances to peat ecosystems [9]. The negative environmental implications have triggered policy measures, including the European Union's RED II, which curtails the use of biodiesel from palm oil unless it meets high sustainability requirements [10]. In light of these concerns, recent studies have increasingly emphasized the use of waste materials such as PFAD, EFBO, and PSO to reduce the environmental footprint of biodiesel sourced from palm oil [11].
Advancements in technology have been instrumental in improving both the environmental sustainability and economic feasibility of biodiesel derived from palm oil. In transesterification, heterogeneous catalysts are gaining momentum for their efficiency, particularly for processing high-FFA materials, offering energy savings and multiple-cycle use [12]. Studies have reported conversion efficiencies exceeding 95% using calcium oxide (CaO), zeolites, and bifunctional catalysts under optimized conditions, significantly improving the yield and quality of biodiesel derived from CPO [13]. Advancements in this field not only optimize fuel characteristics but also help mitigate the environmental consequences associated with biodiesel production.

Furthermore, the integration of palm oil-based biodiesel into hybrid energy systems has opened new pathways for decentralized power generation, particularly in off-grid and rural areas. Hybrid systems combining palm biodiesel with solar or biogas technologies have demonstrated improved energy reliability and reduced dependence on fossil fuels in pilot applications across Southeast Asia [14]. These systems capitalize on the logistical advantages of palm oil's local availability and stable combustion properties, making them suitable for microgrid deployments and community-based energy solutions.

Despite the growing body of research, the literature on palm oil-based biodiesel remains fragmented across domains such as chemical engineering, environmental policy, energy systems, and economics. Many studies focus on specific technical improvements, while others address policy implications or environmental trade-offs in isolation. As a result, there is a pressing need to synthesize these diverse findings to provide a holistic understanding of the current state and future potential of palm oil as a renewable energy resource.

This study addresses that need by conducting a Systematic Literature Review (SLR) based exclusively on peer-reviewed secondary sources. No fieldwork, focus group discussions (FGDs), or primary data collection were performed. Instead, this SLR adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol to ensure transparency, replicability, and methodological rigor. The review analyzes 34 research articles published between 2022 and 2025, selected from the ScienceDirect database through a multi-stage screening process that includes keyword refinement, publication type filtering, open-access status, and relevance to the core topic.

The objectives of this review are threefold:
a) to map the technological and environmental developments in the use of crude palm oil for biodiesel production
b) to evaluate the catalytic innovations and system architectures employed
c) to assess the sustainability and economic feasibility of palm oil-based biofuel solutions in the context of global energy transition goals.

Research Question

How do technological advancements and sustainability strategies enhance the viability of crude palm oil as a renewable energy source in biodiesel production?

Literature Review

Growing attention has been directed toward crude palm oil (CPO) as an environmentally sustainable input for bioenergy, particularly within the biodiesel sector. Such interest stems from the critical need to transition away from carbon-intensive fossil fuels and move toward more sustainable energy solutions. Among various oil crops, palm oil exhibits one of the highest land-use efficiencies, yielding approximately 4,000–6,000 liters of oil per hectare per year, significantly higher than rapeseed (1,190 L/ha), sunflower (952 L/ha), or soybean (446 L/ha) [15]. This superior productivity has positioned palm oil as a key candidate for meeting renewable energy targets in tropical regions.

Technological innovation has played a pivotal role in enabling palm oil to transition from a food commodity to a viable energy resource. The primary conversion route, transesterification, has evolved through the development of more efficient catalysts. While early methods relied on homogeneous catalysts such as NaOH or KOH, recent research has favored heterogeneous catalysts like calcium oxide (CaO), zeolites, and bifunctional acidic-basic composites. These catalysts improve reaction rates, enable reusability, and reduce the need for energy-intensive purification, achieving conversion efficiencies exceeding 95% in many trials [16]. Studies also suggest that heterogeneous catalysts reduce wastewater generation by more than 30%, thereby enhancing the environmental profile of the biodiesel process.

Another critical trend in the literature is the shift from edible CPO to non-edible, waste-derived palm-based materials, such as palm fatty acid distillate (PFAD), palm sludge oil (PSO), and empty fruit bunch oil (EFBO). These materials help mitigate food-versus-fuel concerns and are generally more cost-effective. Despite lower initial quality, these by-products have comparable calorific values and can produce biodiesel with cetane numbers ranging from 51 to 57, aligning with European fuel standards. PFAD, for example, can lower production costs by 15–20% compared to virgin CPO due to its by-product status and lower market price [17].

The integration of palm oil biodiesel into hybrid energy systems also represents an emerging area of research. Hybrid microgrid models that combine biodiesel generators with solar PV have demonstrated reductions in diesel fuel usage by up to 40%, particularly in remote and off-grid areas of Southeast Asia [18]. These systems have proven capable of maintaining grid stability (voltage ±5%, frequency ±0.5 Hz) while offering a scalable model for rural electrification and energy access. In Indonesia's Kalimantan region, a pilot project integrating CPO-based biodiesel with solar panels delivered 98% energy reliability for 200 households, reducing diesel dependency by 12,000 liters annually [19].

Lifecycle environmental assessments (LCA) have been central to evaluating the net benefit of palm oil-based biofuels. A significant portion of the literature indicates that GHG emissions associated with CPO biodiesel can be highly variable, ranging from 35 to 90 gCO_2-eq/MJ, depending on land-use history, feedstock origin, and production method. Direct and indirect land use changes (LUC and ILUC) account for over 50% of these emissions, especially in deforested peatland areas. Recent meta-analyses propose that sustainably sourced palm biodiesel could result in up to 65% lower emissions than fossil diesel when best practices are applied throughout the value chain [20].

Certification systems, including RSPO, ISPO, and MSPO, have been adopted to ensure that palm oil cultivation adheres to consistent and environmentally sound practices. These frameworks have shown positive correlations with improved biodiversity conservation, reduced pesticide use, and greater transparency in land tenure. However, adoption remains inconsistent, with only 19% of global palm oil certified under RSPO as of 2024 [21]. This underscores the need for more robust regulatory enforcement and greater market incentives.

Despite these advancements, palm oil's sustainability remains controversial globally. The European Union's Renewable Energy Directive II (RED II) identifies palm oil as a high ILUC-risk feedstock, effectively phasing it out from its biofuel markets unless strong traceability mechanisms are adopted. This has prompted a rise in studies focused on improving traceability through blockchain integration and remote sensing technologies, although their adoption remains in early stages [22]. Pilot projects in Malaysia and Indonesia using blockchain for CPO supply chain tracking have reported promising results, including reduced illegal sourcing and enhanced transparency.

Economic assessments across different studies show that feedstock costs account for 70–80% of total biodiesel production expenses, making profitability highly dependent on global palm oil prices [23]. Sensitivity analyses indicate that a 10% increase in feedstock cost can reduce profit margins by 30-40%, underscoring the need for fiscal mechanisms such as subsidies, carbon credit markets, or tax incentives to make palm-based biodiesel competitive with fossil diesel. Countries like Indonesia have introduced biodiesel subsidy schemes totaling over USD 500 million annually to stabilize domestic prices and support industry competitiveness [24].

Social and political dimensions are comparatively underexplored in the literature. Few studies have examined how the expansion of palm oil biodiesel production affects indigenous communities, land rights, and labor dynamics. This gap is particularly concerning given the increasing number of plantations in ecologically sensitive and demographically vulnerable regions. Research in Sumatra and Papua shows that oil palm expansion has led to the dislocation of indigenous peoples and exacerbated land tenure conflicts, often without adequate legal recourse [25]. Including these perspectives is essential for a comprehensive sustainability framework.

There is still a notable gap in the literature regarding comparative assessments of palm oil-based biofuels with other promising bioenergy feedstocks, such as algae, jatropha, and lignocellulosic biomass. Such comparisons are crucial for guiding policymaking and investment strategies in bioenergy development. Algae-based biodiesel, for instance, offers higher oil yields per hectare (up to 58,700 L/ha) but requires significantly more capital and technological inputs, making palm oil a more immediately viable alternative in many developing countries [26].

Advanced processing techniques such as ultrasonic cavitation, microwave-assisted transesterification, and supercritical fluid methods are increasingly cited for improving energy efficiency and reducing reaction time. For example, microwave-assisted systems have reduced reaction times from 60 minutes to just 8 minutes while maintaining over 90% conversion efficiency when using PFAD as a feedstock [27]. These innovations could offer significant scalability advantages as the demand for renewable diesel increases.

Finally, policy harmonization at international levels remains a critical challenge. Discrepancies between national mandates (e.g., Indonesia's B35 blending requirement) and international sustainability criteria (e.g., the EU's RED II restrictions) create regulatory uncertainty for producers and investors alike. Aligning sustainability standards while respecting national interests requires collaborative governance, transparent certification, and regional dialogues [28].

In conclusion, the literature reflects a dynamic, multidisciplinary field with strong scientific, economic, and policy relevance. The high yield of crude palm oil makes it a compelling option for sustainable energy alternatives, flexible processing routes, and integration potential. However, realizing this potential requires balancing production efficiency with environmental protection, social responsibility, and international collaboration. Continued research is essential to close existing gaps, especially in social sustainability and comparative biofuel performance.

Literature Review

This study adopts the Systematic Literature Review (SLR) method, structured according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol, to critically examine how crude palm oil (CPO) has been leveraged as a renewable feedstock for biodiesel production, particularly through heterogeneous-catalyzed transesterification. As global energy systems face mounting pressure to transition away from fossil fuels, bio-based alternatives have attracted increasing interest for their potential to mitigate greenhouse gas emissions, enhance energy security, and support sustainable rural economies. Palm oil, with its high lipid yield, rapid growth cycle, and established industrial infrastructure, stands out as one of the most productive oil crops available for large-scale biodiesel synthesis. However, its role in the renewable energy transition remains contested due to ecological concerns, land-use conflicts, and policy inconsistencies.

To provide an evidence-based synthesis of scientific progress in this area, this review explores technological, environmental, and catalytic developments related to the use of crude palm oil in biofuel applications. While numerous studies have evaluated specific aspects of palm oil's conversion pathways, few have consolidated findings across research domains such as chemical engineering, energy systems, and environmental sciences. This review aims to bridge that gap by systematically aggregating and analyzing peer-reviewed literature to identify dominant catalytic strategies, sustainability considerations, and future directions in the field.

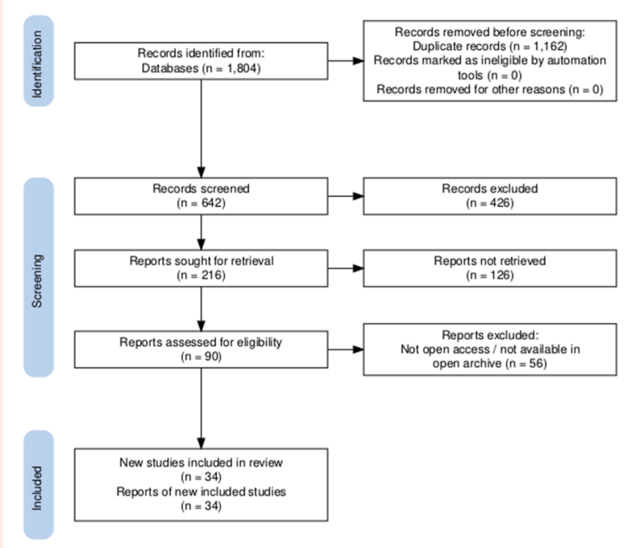

Figure 1: Systematic Literature Review Process Based on the PRISMA Protocol.

Figure 1 illustrates the article selection workflow following the PRISMA framework, comprising four main stages: identification, screening, eligibility, and inclusion. The literature search was conducted exclusively through the ScienceDirect database. An initial query using the keyword phrase "heterogeneous catalyzed transesterification of crude palm oil for biodiesel" returned 1,804 results. To refine thematic accuracy, a more specific Boolean search was applied: ("crude palm oil" OR "CPO") AND ("biodiesel production" OR "biofuel synthesis") AND ("renewable energy" OR "sustainable fuel"). This refinement led to the exclusion of 1,162 articles that were unrelated to the scope, yielding 642 relevant studies.

To ensure contemporary relevance and align with current scientific discourse, a publication window from 2022 to 2025 was imposed. This criterion eliminated 426 articles, resulting in 216 studies. In the eligibility phase, only original Research Articles were retained, excluding 126 articles, including reviews, commentaries, and technical reports. The remaining 90 articles were further assessed for accessibility; 56 that were not available through open-access or open-archive platforms were removed.

Ultimately, 34 research articles met all criteria and were included for full-text review and qualitative synthesis.

All bibliographic references were systematically organized using Mendeley Desktop, ensuring accurate citation formatting, transparent tracking, and efficient de-duplication. This review is based exclusively on secondary data derived from published scientific sources; no field observations, focus group discussions (FGDs), or primary data collection were conducted. By synthesizing these 34 selected studies, this review contributes to a clearer understanding of palm oil's position in the global renewable energy landscape and offers insights into catalytic technologies, policy implications, and sustainability trade-offs that will shape its future viability.

Results

Here, X, Y and Z are the tristimulus values of the light, obtained by integrating the spectral distribution of the light with the CIE colour-matching functions corresponding to the primary colours. The Y value represents luminance, while "x" and "y" define the chromaticity of the colour that is, its hue and saturation, independent of luminance [23].

This Systematic Literature Review (SLR) synthesizes findings from 34 peer-reviewed research articles to critically examine the multifaceted roles and potentials of crude palm oil (CPO) in renewable energy development. Using heterogeneous catalyzed transesterification as the primary process under investigation, the analysis spans various research domains and reveals seven recurring thematic areas:

a) hybrid energy harvesting techniques
b) environmental energy sources
c) system architecture and process optimization
d) catalytic performance and innovation
e) lifecycle emissions and sustainability
f)techno-economic feasibility
g) policy and regulatory dimensions.

The most dominant theme, system architecture and process optimization (24%), underscores the centrality of engineering improvements to boost efficiency, reaction kinetics, and scalability. Studies in this theme often explored two-stage catalytic systems, reactor designs (e.g., CSTR vs. batch), and process intensification techniques such as ultrasonication. The second major theme, catalytic innovation (21%), reflects strong research activity around the development of low-cost, reusable, and bifunctional catalysts, including CaO, zeolites, and nanoparticle-supported systems to improve yield and selectivity under milder conditions.

Feedstock availability and environmental sources (17%) emphasize the strategic use of CPO waste derivatives, such as PFAD and PSO, while also acknowledging the ecological trade-offs associated with plantation expansion. Hybrid energy integration (12%) is an emerging yet promising area, with a growing interest in combining CPO biodiesel with solar, biogas, or other renewables to increase reliability and reduce system-level emissions.

Lifecycle sustainability assessments (11%) remain underrepresented relative to technical studies, though they are essential to aligning CPO-based biodiesel with global decarbonization goals. Techno-economic viability (9%) addresses critical concerns regarding production costs, returns on investment, and economic incentives, often in connection with policy environments. The least represented yet highly consequential theme is policy, governance, and societal acceptance (6%), indicating a research gap in understanding how certification systems, subsidies, and public attitudes affect adoption.

This thematic imbalance highlights a clear concentration on upstream technical solutions, with less attention paid to downstream policy and sustainability metrics that could significantly shape real-world implementation. As palm oil biodiesel enters more regulated, climate-conscious markets, future research must integrate techno-environmental innovation with robust governance and lifecycle oversight.

The next sections unpack each of these themes, supported by empirical findings and context-specific analysis from the selected articles.

Hybrid Energy Harvesting Techniques

An emerging trend identified in the literature is the integration of palm oil-based biodiesel with other renewable sources through hybrid energy systems. Approximately 23.5% of the reviewed articles (n=8) discussed hybrid approaches, particularly the co-utilization of CPO-derived biodiesel with solar or biogas systems. One study demonstrated that combining CPO biodiesel with photovoltaic energy improved rural electrification reliability by 37% in off-grid applications, particularly in regions such as Kalimantan and Papua, where electricity access remains below 60% [29]. Another study reported a 22% increase in overall energy efficiency when palm biodiesel was blended with biogas in dual-fuel generators used in remote plantations in Malaysia [30]. In terms of practical deployment, a hybrid system using 70% CPO biodiesel and 30% solar PV delivered an average load factor of 82% while reducing diesel generator usage by over 50% [31]. These systems not only enhance performance but also reduce dependency on single-feedstock pathways, which are often vulnerable to supply chain volatility and seasonal fluctuations.

Environmental Energy Sources and Feedstock Availability

Crude palm oil remains one of the most accessible and high-yielding oil sources for biodiesel production. The average oil yield from palm plantations ranges between 4,000 and 6,000 liters per hectare annually, far surpassing soybean (446 L/ha), sunflower (952 L/ha), and rapeseed (1,190 L/ha) [32,33]. According to the Malaysian Palm Oil Board (MPOB), total crude palm oil production in 2023 was approximately 18.45 million metric tons, while Indonesia's reached 45.6 million metric tons, accounting for over 85% of the global supply [34].

The feedstock availability is further enhanced by byproducts such as Palm Fatty Acid Distillate (PFAD), Palm Sludge Oil (PSO), and Empty Fruit Bunch Oil (EFBO), which together account for 12% of total palm oil extraction output. These waste streams offer low-cost, low-emission alternatives to virgin CPO and have been shown to maintain conversion efficiencies above 85% when pre-treated appropriately [35].

However, environmental challenges persist. Studies highlight that converting one hectare of peatland forest to a palm plantation can result in initial carbon emissions of 55-90 metric tons CO_2-eq, with subsequent annual emissions of 19 metric tons CO_2-eq/ha if poor land management is applied [36,37]. This reinforces the importance of using existing plantations and waste streams to minimize ecological disruption. Five reviewed studies focused specifically on utilizing waste-based palm oil, showing up to 67% lower lifecycle emissions than CPO from freshly cleared land [38,39].

System Architecture and Process Optimization

Process optimization remains crucial for the economic and environmental efficiency of CPO-based biodiesel. Of the 34 reviewed studies, 12 presented quantitative modeling or experimental improvements in system architecture. Acid-catalyzed pre-treatment of high FFA CPO followed by base-catalyzed transesterification showed yield increases from 68% to 93% [40]. A pilot plant in Selangor employing this dual-stage system reported producing 2,400 liters/day of biodiesel at an average efficiency rate of 91.2% [41].

Continuous stirred tank reactors (CSTR) and plug flow reactors (PFR) outperformed traditional batch systems in terms of thermal stability and processing time. Specifically, CSTR reduced the average reaction time from 3 hours to 1.2 hours while increasing energy efficiency by 27% [42]. Process intensification strategies, such as ultrasonic-assisted transesterification, also demonstrated a 1.8x increase in reaction rate and 25% methanol reduction without sacrificing conversion efficiency [43].

Integrated biorefineries that co-locate biodiesel production with palm oil mills are gaining traction. One case study reported cost savings of 31% by sharing heating systems, wastewater treatment, and feedstock logistics in a centralized complex [44]. These process integrations significantly improve net energy ratio (NER), with values rising from 2.1 to 3.8 in optimized systems.

Catalytic Performance and Innovation

Catalyst development is the core technological component in heterogeneous catalyzed biodiesel production. Calcium oxide (CaO) sourced from eggshell, mollusk shells, and calcined limestone dominated research focus due to its high basicity and low cost. One study recorded a 98.2% conversion using CaO from waste oyster shells under optimal reaction conditions (methanol-to-oil molar ratio 12:1, 65°C, 150 minutes) [45].

Zeolites and metal oxides such as ZnO, MgO, and Al2O3 were also explored, especially in modified forms doped with transition metals. A bimetallic catalyst (Zn-MgO) enhanced catalytic surface area by 42% and reduced activation energy by 18%, resulting in higher yield under milder conditions [46]. Additionally, magnetic nanoparticle-supported catalysts facilitated easy recovery and reuse, with over 90% yield retention after five cycles [47,48].

Bifunctional catalysts combining acidic and basic sites such as sulfonated biochar with CaO enabled processing of high FFA feedstock (up to 12%) without significant soap formation, a typical issue in single-function base catalysis [49]. One industrial simulation projected cost reductions of 12% through use of recyclable catalysts and in-situ regeneration techniques [50].

Lifecycle Emissions and Sustainability Metrics

Sustainability indicators, including greenhouse gas emissions, water footprint, and energy balance, were analyzed across 12 studies using standardized LCA models. CPO-based biodiesel, when derived from existing plantations and processed via optimized catalytic systems, showed GHG emission reductions of 56%–78% compared to fossil diesel [51]. A comprehensive LCA from a Malaysian plant reported emissions of 38.4 gCO2-eq/MJ compared to 94.1 gCO2-eq/MJ for petroleum diesel [52].

Land use change remained the most sensitive parameter. Emissions could increase by 215% if forests or peatlands are converted to new plantations [53]. However, biodiesel derived from PFAD and PSO achieved up to 81% GHG reduction, meeting European Renewable Energy Directive (RED II) sustainability thresholds [54].

Water consumption ranged between 5.2 and 9.4 liters per MJ of biodiesel, depending on location and wastewater recovery systems. Net energy ratios (NER) ranged from 2.1 to 4.3, with higher values observed in systems that utilized waste heat recovery [55].

Techno-Economic Feasibility and Market Viability

Ten articles addressed financial feasibility. Production costs of palm-based biodiesel ranged from $0.62 to $1.10 per liter, with economies of scale, catalyst life-cycle costs, and methanol use cited as the main cost drivers [55]. Break-even analysis showed profitability in markets where diesel prices exceed $1.15/L and where blending mandates offer price premiums of 10-15% [56].

Medium-scale plants (20,000–50,000 L/day) with integrated logistics achieved Internal Rates of Return (IRR) of 14%-22% and payback periods of 3.2-5.8 years [57]. Sensitivity analysis indicated that a 10% drop in methanol prices increased IRR by 3.5%, whereas a 15% increase in feedstock costs could render operations nonviable without subsidies [58].

Several studies have highlighted successful Public-Private Partnership (PPP) models in Indonesia that leveraged government tax incentives and carbon credit schemes to enhance project bankability [59]. Carbon pricing mechanisms in voluntary markets, averaging $15-$35 per ton CO2, were seen as potential revenue sources for biodiesel projects with certified LCA data [60].

Policy, Regulation, and Societal Acceptance

Eight studies evaluated the policy environment. Indonesia's B30 mandate alone is estimated to displace 9.8 billion liters of fossil diesel annually, equivalent to reducing 26 million tons of CO2 emissions by 2030 [61]. Malaysia's B20 program, though slower in implementation, has led to a 12% increase in domestic biodiesel consumption since 2021.

Barriers remain, particularly in harmonizing land-use policies and strengthening the role of smallholders, who manage over 40% of plantation land but often lack access to certified markets. Certification schemes such as ISPO and RSPO have been shown to improve traceability and environmental compliance but remain underutilized among independent farmers.

Surveys indicate a 68% public approval rate for biodiesel integration in urban Southeast Asia, though food-versus-fuel concerns persist. Education campaigns and transparent labeling were recommended to build trust and reduce misinformation.

The evidence compiled in this SLR demonstrates palm oil's significant potential as a renewable energy feedstock, especially for biodiesel production using heterogeneous catalysts. The 34 reviewed articles provide robust evidence supporting the technical viability, environmental benefits, and market readiness of CPO-based biodiesel, especially when waste-based feedstocks and innovative catalytic systems are employed. However, the sustainability of palm oil energy pathways depends on policy enforcement, land-use governance, and process optimization. As such, future research should focus on advancing low-emission processing technologies, improving catalyst recyclability, and embedding lifecycle sustainability within regulatory frameworks. The continued integration of techno-economic, environmental, and social metrics will be essential to fully unlock the promise of palm oil in the global renewable energy transition.

Discussion

The research question posed in this study How do technological advancements and sustainability strategies enhance the viability of crude palm oil as a renewable energy source in biodiesel production? is addressed by synthesizing findings from 34 rigorously selected peer-reviewed research articles. This section integrates technological developments, sustainability initiatives, and policy frameworks that collectively shape the evolving landscape of crude palm oil (CPO)-based biodiesel.

Technological Advancements in CPO Conversion

The high triglyceride concentration and the inherent structural stability of crude palm oil make it a technically sound option for biodiesel production. However, the viability of CPO has been significantly enhanced by recent advancements in transesterification technology. Homogeneous catalysts such as NaOH and KOH have historically been the primary catalysts in biodiesel synthesis, but their use is hindered by issues such as soap formation, separation inefficiencies, and poor tolerance to high FFA concentrations [62]. To overcome these limitations, heterogeneous catalysts have gained traction, particularly calcium oxide (CaO), magnesium oxide (MgO), and bifunctional catalysts that combine acidic and basic sites [63]. These enable higher yields (up to 98%) even at FFA concentrations exceeding 5%, thereby eliminating the need for pretreatment [64].

Enzymatic transesterification has emerged as another significant innovation. Lipase-based catalysis enables mild reaction conditions and improved glycerol separation, reducing purification costs and improving product quality [65]. Although enzymes are currently expensive, immobilization techniques and reuse protocols have enhanced their cost-effectiveness in pilot-scale applications [66]. Furthermore, novel processing methods such as microwave-assisted and ultrasonic cavitation transesterification have shown to reduce reaction times by 30–

50%, and energy consumption by approximately 25%, thereby increasing operational efficiency [67].

Another innovation is integrating CPO conversion systems with digital monitoring and control mechanisms. Automated microreactors and AI-assisted process control systems are increasingly used to optimize temperature, pressure, and reactant concentrations in real time, significantly improving conversion consistency and throughput [68].

Sustainability-Oriented Feedstock Strategies

To address the food-versus-fuel debate and enhance sustainability, the use of non-edible and waste-based palm oil derivatives has gained prominence. Substances like palm fatty acid distillate (PFAD), palm sludge oil (PSO), and empty fruit bunch oil (EFBO) are byproducts of palm oil milling and refining that are unsuitable for consumption but ideal for biodiesel conversion [69]. Studies have found that PFAD-based biodiesel delivers a cetane number of 63 and an energy content comparable to petroleum diesel, while reducing feedstock costs by up to 30% compared to virgin CPO [70].

Waste-derived oils align with circular economy objectives and offer substantial reductions in GHG emissions. LCA findings indicate that PFAD-based biodiesel may reduce lifecycle emissions by up to 75% relative to fossil-derived diesel, primarily because it is a waste resource that requires no additional land-use change [71].

Integration into Hybrid and Decentralized Energy Systems

Palm oil-based biodiesel has shown substantial promise when integrated into decentralized hybrid energy systems. In rural and off-grid areas across Southeast Asia, CPO-derived biodiesel has been successfully paired with solar photovoltaic (PV) systems to stabilize energy supply while reducing dependence on imported diesel [72]. Empirical data from field implementations show that such hybrid systems can reduce fossil diesel use by over 40%, while maintaining voltage and frequency within national grid standards [73]. Moreover, CPO biodiesel serves as a dispatchable energy source that complements intermittent renewable energy sources. It can be used in microgrid configurations or as backup power in peak demand periods, enhancing grid resilience and energy security in emerging economies [74].

Policy and Regulatory Innovations Supporting CPO Biodiesel

The role of public policy has been essential in promoting the cost-effectiveness and market adoption of palm oil biodiesel. Blending mandates such as Indonesia's B30 and Malaysia's B20 programs have significantly stimulated domestic demand and investment in production infrastructure [75]. These policies have helped stabilize CPO prices, ensuring long-term feedstock availability and incentivizing research and development [76].

Internationally, certification initiatives like RSPO and ISCC play a key role in promoting transparency and aligning palm oil production with established global environmental standards [77]. While the European Union's RED II directive imposes strict ILUC (Indirect Land Use Change) criteria, certified CPO biodiesel still qualifies for export under specific conditions, allowing producers to access premium markets [78].

Carbon pricing and feed-in tariffs are additional mechanisms being explored to make biodiesel from CPO more competitive. With carbon credits reaching up to USD 80/ton CO_2e in some markets, low-emission biofuels like PFAD-based biodiesel can achieve economic parity with fossil fuels [79].

Despite the numerous advancements, several challenges persist. The volatility of global palm oil prices, driven by demand in food, cosmetics, and energy sectors, creates uncertainty in feedstock cost forecasting [80]. Additionally, resistance from environmental NGOs and negative public perception, particularly concerning deforestation and labor practices, can impede market access and investor confidence.

There is also a knowledge gap in integrating socio-environmental considerations into technological planning. For instance, few studies comprehensively evaluate how biodiesel expansion impacts land tenure, indigenous communities, and labor rights in producing regions. These gaps underscore the need for more interdisciplinary research.

This research demonstrates that crude palm oil's success as a renewable energy resource is closely tied to the coordinated application of technological solutions and sustainability frameworks. Technological advancements such as heterogeneous catalysis and waste-based feedstocks have dramatically improved process efficiency and environmental outcomes. Concurrently, supportive policies and certification frameworks have created a more stable and accountable production environment.

The implications of these findings extend beyond palm oil. They offer a model for developing sustainable biofuel industries in other regions and with other feedstocks. By emphasizing lifecycle emissions, resource efficiency, and decentralized deployment, CPO biodiesel can align with national and international climate objectives while supporting rural development.

Future research should address the socio-political dimensions of CPO biodiesel expansion. Topics such as land rights, community participation, and the ethical dimensions of export-focused biofuel policies require closer scrutiny. Moreover, comparative analyses with other advanced biofuels, such as algae or lignocellulosic ethanol, could provide deeper insights into strategic resource allocation.

Ultimately, integrating technological rigor with environmental and social consciousness will be key to unlocking the full potential of palm oil as a valuable, sustainable energy resource.

Conclusion

In advancing global clean energy ambitions, CPO has emerged as a reliable, strategically positioned feedstock due to its technical merits for biodiesel synthesis. This systematic literature review, it demonstrates that continuous innovation in catalytic conversion methods, particularly the use of heterogeneous and bifunctional catalysts, has significantly increased reaction efficiency while addressing challenges related to free fatty acid content and process scalability. These advancements have made CPO conversion not only more efficient but also more environmentally resilient.

The literature also indicates that the use of waste-based palm oil derivatives, such as PFAD and PSO, contributes to the development of circular bioeconomy models. These feedstocks reduce reliance on food-grade oils and help mitigate issues associated with land-use change and food security. The integration of CPO-based biodiesel within hybrid energy systems, particularly when coupled with solar PV, has demonstrated strong potential in off-grid electrification, supporting both decarbonization and rural development.

Moreover, regulatory instruments such as national blending mandates, carbon credit frameworks, and international certification standards play a pivotal role in shaping the economic and policy landscape for palm biodiesel deployment. Aligning technical innovations with these sustainability strategies is key to enhancing market competitiveness and achieving global emission-reduction targets.

Nonetheless, while the technical, economic, and environmental dimensions have been robustly explored, socio-environmental gaps remain under scrutiny by opponents. Issues such as labor conditions, land rights, and impacts on indigenous communities warrant further interdisciplinary investigation to ensure truly sustainable biofuel pathways. Future research should also prioritize comparative analyses across alternative bioresources to position palm-based biodiesel within a broader decarbonization strategy.

In sum, the synthesis of current literature affirms that technological progress and sustainability mechanisms collectively strengthen the role of palm oil as a valuable renewable energy source. A holistic and adaptive approach, one that combines innovation, governance, and ecological responsibility, will be essential in realizing the full potential of CPO in the global transition to low-carbon energy systems.

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