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UNLOCKING THE POTENTIALS OF PALM OIL AS A SOURCE OF RENEWABLE ENERGY

LIBERANDO O POTENCIAL DO ÓLEO DE PALMA COMO FONTE DE ENERGIA RENOVÁVEL

DESBLOQUEANDO EL POTENCIAL DEL ACEITE DE PALMA COMO FUENTE DE ENERGÍA RENOVABLE

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ABSTRACT

In response to the global push for cleaner energy solutions, efforts have expanded to explore renewable alternatives beyond conventional sources, with impressive yield levels and multifaceted utility. There is growing acceptance of palm oil as a practical renewable energy resource. This study aims to comprehensively evaluate the potential of palm oil in contributing to renewable energy development. Employing a qualitative literature review methodology, this research systematically synthesizes findings from academic articles, policy documents, and technical reports published between 2015 and 2025. Data collection involved extensive database searches using keywords related to palm oil, renewable energy, biodiesel, and biomass. The gathered literature was analyzed through thematic content analysis to identify key trends, challenges, and opportunities in palm oil utilization for energy purposes. Results indicate that palm oil-based biodiesel and biogas from biomass residues offer substantial renewable energy outputs with favorable energy return on investment. However, sustainability concerns, including deforestation, land use change, and fragmented governance frameworks, pose significant obstacles. Technological limitations and regulatory inconsistencies also hinder optimal resource exploitation. In conclusion, while palm oil holds considerable promise as a renewable energy source, strategic policy integration, enhanced sustainability certification, and technological advancements are essential to fully unlock its benefits. Future research should focus on empirical assessments of smallholder engagement and lifecycle environmental impacts to support more inclusive and sustainable bioenergy practices.

Keywords: Palm Oil. Renewable Energy. Biodiesel. Biomass. Qualitative Literature Review.

RESUMO

Em resposta à pressão global por soluções energéticas mais limpas, os esforços têm se expandido para explorar alternativas renováveis além das fontes convencionais, com níveis de rendimento impressionantes e utilidade multifacetada. Há uma crescente

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aceitação do óleo de palma como um recurso prático de energia renovável. Este estudo visa avaliar de forma abrangente o potencial do óleo de palma em contribuir para o desenvolvimento de energias renováveis. Empregando uma metodologia de revisão qualitativa da literatura, esta pesquisa sintetiza sistematicamente os resultados de artigos acadêmicos, documentos de políticas e relatórios técnicos publicados entre 2015 e 2025. A coleta de dados envolveu extensas buscas em bancos de dados usando palavras-chave relacionadas a óleo de palma, energia renovável, biodiesel e biomassa. A literatura coletada foi analisada por meio de análise de conteúdo temática para identificar as principais tendências, desafios e oportunidades na utilização do óleo de palma para fins energéticos. Os resultados indicam que o biodiesel e o biogás à base de óleo de palma a partir de resíduos de biomassa oferecem resultados substanciais de energia renovável com retorno energético favorável sobre o investimento. No entanto, preocupações com a sustentabilidade, incluindo desmatamento, mudanças no uso da terra e estruturas de governança fragmentadas, representam obstáculos significativos. Limitações tecnológicas e inconsistências regulatórias também dificultam a exploração ideal dos recursos. Em conclusão, embora o óleo de palma seja uma fonte de energia renovável bastante promissora, a integração de políticas estratégicas, a certificação de sustentabilidade aprimorada e os avanços tecnológicos são essenciais para liberar plenamente seus benefícios. Pesquisas futuras devem se concentrar em avaliações empíricas do engajamento de pequenos produtores e dos impactos ambientais ao longo do ciclo de vida, a fim de apoiar práticas de bioenergia mais inclusivas e sustentáveis.

Palavras-chave: Óleo de palma. Energia renovável. Biodiesel. Biomassa. Revisão qualitativa da literatura.

RESUMEN

En respuesta al impulso global por soluciones energéticas más limpias, se han expandido los esfuerzos para explorar alternativas renovables más allá de las fuentes convencionales, con impresionantes niveles de rendimiento y una utilidad multifacética. El aceite de palma está cada vez más aceptado como una fuente práctica de energía renovable. Este estudio busca evaluar exhaustivamente el potencial del aceite de palma para contribuir al desarrollo de las energías renovables. Mediante una metodología cualitativa de revisión bibliográfica, esta investigación sintetiza sistemáticamente los hallazgos de artículos académicos, documentos de políticas e informes técnicos publicados entre 2015 y 2025. La recopilación de datos implicó búsquedas exhaustivas en bases de datos utilizando palabras clave relacionadas con el aceite de palma, las energías renovables, el biodiésel y la biomasa. La literatura recopilada se analizó mediante un análisis de contenido temático para identificar tendencias, desafíos y oportunidades clave en el uso del aceite de palma con fines energéticos. Los resultados indican que el biodiésel y el biogás a base de aceite de palma a partir de residuos de biomasa ofrecen importantes fuentes de energía renovable con una rentabilidad energética favorable. Sin embargo, las preocupaciones sobre la sostenibilidad, como la deforestación, el cambio de uso del suelo y la fragmentación de los marcos de gobernanza, plantean obstáculos significativos. Las limitaciones tecnológicas y las inconsistencias regulatorias también dificultan la explotación óptima de los recursos. En conclusión, si bien el aceite de palma ofrece un gran potencial como fuente de energía renovable, la integración estratégica de políticas, una mayor certificación de sostenibilidad y los avances tecnológicos son esenciales para aprovechar al máximo sus beneficios. Las investigaciones futuras deberían centrarse en evaluaciones empíricas de la participación de los pequeños productores y los impactos ambientales a lo largo del ciclo de vida para impulsar prácticas bioenergéticas más inclusivas y sostenibles.

Palabras Clave: Aceite de palma. Energía renovable. Biodiésel. Biomasa. Revisión cualitativa de la literatura.

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INTRODUCTION

The global transition toward sustainable energy has intensified amid escalating climate change concerns, volatile fossil fuel markets, and the urgent imperative to cut down on greenhouse gas (GHG) emissions. As the world moves toward decarbonization, the transition toward renewables is pivotal in securing long-term energy supply and fulfilling environmental sustainability targets (Dirisu et al., 2024). While solar, wind, and hydropower dominate global discourse, bioenergy continues to attract considerable attention, especially in the Global South, due to its potential to simultaneously drive rural development and act as a cleaner option to reduce the need for energy produced from fossil fuels (Yana et al., 2022).

Bioenergy, particularly liquid biofuels derived from biomass, is gaining momentum as a key strategy in national energy roadmaps. Vegetable oil-sourced biodiesel has proven to be a feasible diesel substitute for use in mobility and industrial operations (Silalahi et al., 2020). In the Southeast Asian context, palm oil has become a primary raw material for biodiesel manufacture, largely due to its superior yield per unit area, low production costs, and year-round availability (Suhara et al., 2024). The international palm oil industry is primarily led by Indonesia and Malaysia, which jointly produce the vast majority, exceeding 85%, making them pivotal actors in the bioenergy landscape (Naidu & Moorthy, 2021). The increasing reliance on palm-based biofuels has sparked both optimism and controversy, balancing economic opportunity with ecological risk.

Within energy diversification frameworks, palm oil emerges as a key asset in the renewable energy portfolio. Its conversion into biodiesel, biogas, and bioethanol has been enabled through both first-generation and emerging second-generation technologies (Alfarizi et al., 2023). These applications are crucial for reducing dependency on imported petroleum, especially in countries with significant agricultural output but limited fossil fuel reserves (Pehnelt & Vietze, 2013). In addition, initiatives like Indonesia's B30 mandate and the European Union's RED II have intertwined palm oil with both climate action policies and international trade politics (Farobie & Hartulistiyoso, 2022). Despite this, debates surrounding deforestation, biodiversity loss, land tenure conflicts, and food security have complicated the expansion of palm oil-based energy (Mayr et al., 2021).

Environmental critics argue that large-scale oil palm plantations have exacerbated tropical deforestation, especially in ecologically sensitive zones (Carlson et al., 2013). Expansion of palm plantations causing land-use changes has raised some concerns about carbon emissions that might counteract biofuels' environmental promises (Kusin et al., 2017). Furthermore, conversion of forests and peatlands into monoculture plantations may undermine carbon sequestration, disrupts ecosystem services, and accelerates habitat fragmentation (Sumarga et al., 2016). Growing sustainability concerns have spurred the development of both voluntary and regulatory schemes like RSPO, ISPO, and MSPO (Abdul Majid et al., 2021).

Simultaneously, the potential of palm oil to support rural growth is substantial, energy equity, and poverty alleviation particularly when production is integrated with smallholder systems (Dharmawan et al., 2021). A significant number of rural households rely primarily on palm cultivation for their economic sustenance, and integrating these producers into sustainable energy markets could yield significant socio-economic dividends (Mayarni et al., 2025). However, weak governance structures, inconsistent policy enforcement, and inadequate capacity among smallholders continue to hinder inclusive participation in the bioenergy transition (Petri et al., 2024).

Technological progress has played a dual role by increasing energy efficiency and decreasing environmental degradation in palm oil processing. Advances in biorefinery technologies, capturing methane emissions from palm oil mill effluent (POME), and integrated waste-to-energy systems offer promising pathways for sustainable energy generation (Louhasakul et al., 2021). Nonetheless, high capital costs and lack of technical expertise have impeded the adoption of these innovations in many regions (Aziz et al., 2020).

Considerations related to geopolitics influence worldwide debates about the use of palm oil for sustainable energy. Under the 'high ILUC-risk' classification, the European Union has implemented import limitations on palm oil used for biofuel, referencing environmental issues (Puah & Lukman, 2025). This move has been met with resistance from producer countries, who view such policies as discriminatory and detrimental to economic development. Palm oil's future in renewable energy depends on a blend of technological, environmental, regulatory, trade, and diplomatic influences (Zainuddin et al., 2025).

Given these multifaceted tensions, there is an urgent need to comprehensively assess the potential offered by palm oil as a renewable energy option assessed through a comprehensive and evidence-based framework. Previous studies have often focused on either environmental critiques or economic potential in isolation, without offering a holistic synthesis. Moreover, the complexity of integrating sustainability, energy policy, and local livelihoods necessitates a structured analytical approach grounded in recent literature.

This study, therefore, aims to conduct a qualitative literature review that critically explores the opportunities and constraints associated with palm oil as a renewable energy feedstock. It seeks to synthesize findings from diverse sources including policy papers, academic journals, and sustainability reports published between 2015 and 2025. The purpose is to present a sophisticated perspective on palm oil's role in advancing renewable energy, while highlighting governance gaps, technological trends, and future research directions. This approach provides a non-empirical yet academically rigorous foundation for policymakers, researchers, and stakeholders engaged in the intersection of energy, environment, and development.

LITERATURE REVIEW

1. The Strategic Role of Palm Oil in Bioenergy Transition

Particularly in Indonesia and Malaysia, palm oil has gained importance as a bioenergy feedstock in Southeast Asia because of its efficient oil production and lower costs compared to other vegetable oils (Harahap et al., 2019). With global demand for low-carbon energy alternatives rising, biodiesel made from crude palm oil (CPO) is progressively accepted as an effective replacement for fossil diesel, contributing to national energy diversification agendas (Ramadhan et al., 2023). National mandates such as Indonesia's B30 blend policy have accelerated industrial uptake of palm-based biodiesel, reinforcing its centrality in regional energy security strategies (Yasinta & Karuniasa, 2021).

2. Sustainability Challenges: Land Use, Biodiversity, and Emissions

Despite its bioenergy potential, palm oil cultivation is mired in controversies surrounding deforestation, peatland degradation, and biodiversity loss, notably when such expansion leads to the loss of primary forests (Zhu et al., 2022). Carbon emissions are substantially impacted by land-use alterations associated with the expansion of oil palm cultivation, often offsetting the climate benefits of palm-based biodiesel (Charters et al., 2019). Under RED II, the European Union's labeling of palm oil as a 'high indirect land-use change risk' feedstock has triggered global controversy over the environmental validity and acceptance of palm-based biofuels in the international green energy sector (Searle & Giuntoli, 2018). Furthermore, greenhouse gas emissions from land clearing and processing residues like palm oil mill effluent (POME) remain underregulated in many jurisdictions (Acobta et al., 2023).

3. Governance and Policy Coherence in Palm Bioenergy Development

Institutional fragmentation and inconsistent regulatory frameworks have hindered the effective governance of palm oil bioenergy in producing countries (Austin et al., 2019). Overlapping land tenure regimes, weak law enforcement, and poor inter-ministerial coordination often lead to policy contradictions between energy, agriculture, and environmental sectors (van Noordwijk et al., 2017). While national certification schemes like ISPO and MSPO have attempted to promote sustainability, they have been critiqued for lacking credibility, transparency, and alignment with international standards (Afrizal et al., 2023). At the same time, structural issues have been addressed only in part by voluntary frameworks like the RSPO, largely owing to their limited scope and segmented market presence (Lyons-White & Knight, 2018).

4. **Technological Innovation and Infrastructure Constraints**

Technological advancements have made it possible to improve the energy consumption efficiency and environmental effects related to bioenergy derived from palm oil. Processes such as transesterification, biogas capture from POME, and biomass gasification have enhanced the energy yield of palm residues while reducing emissions (Peter et al., 2021). The broad implementation of such innovations is commonly hindered by expensive capital requirements, limited technical expertise, and insufficient financial support, particularly for small to medium enterprises (Chew et al., 2020). The advancement of second-generation biofuels utilizing lignocellulosic biomass from palm fronds and empty fruit bunches holds significant potential, but remains underexplored in policy and investment frameworks (Zakaria et al., 2024).

5. **Socioeconomic Implications and Smallholder Inclusion**

The expansion of palm oil-based energy systems presents both risks and opportunities for smallholder farmers. On one hand, bioenergy markets offer an alternative income stream and promote rural electrification in off-grid regions (Tambi et al., 2021). On the other hand, exclusionary policies, land dispossession, and unequal access to technologies may deepen rural inequalities and reinforce corporate domination of bioenergy value chains (Rigg, 2020). Efforts to integrate smallholders into sustainable supply chains require targeted interventions, including training, financial support, and cooperative-based models that align with sustainability certifications (Abideen et al., 2023). Moreover, inclusive governance frameworks are critical for ensuring equitable benefit distribution and minimizing conflict risks (Christian et al., 2024).

6. **Global Trade Dynamics and Future Pathways**

International trade relations significantly influence the prospects of palm oil in renewable energy markets. Export restrictions, tariff structures, and sustainability-based import criteria have reshaped the flow of palm oil products globally, particularly in response to environmental pressures from consumer countries (Pacheco, P.; Gnych, S.; Dermawan, A.; Komarudin, H.; Okarda, 2017). The emerging geopolitical rivalry between producer and consumer nations underscores the need for harmonized sustainability standards and transparent negotiation platforms that balance ecological protection with economic development (Higgins & Richards, 2019).

METHOD

This research applied a qualitative review of existing literature to investigate the advantages and difficulties of harnessing palm oil for renewable energy applications. The qualitative design adopted in this research is interpretivist in nature, emphasizing the critical understanding of concepts, policies, and narratives found within scholarly and policy-oriented texts rather than the collection of empirical field data. As such, the literature review did not follow the rigid structure of a systematic literature review (SLR), but instead prioritized thematic depth, contextual interpretation, and critical synthesis across diverse sources. The main instrument in this qualitative approach was the researcher as the analytical agent, responsible for selecting, interpreting, and connecting meanings within the reviewed materials. Data were collected from academic journal articles, policy briefs, government reports, and international organizational publications published between 2015 and 2025. Sources were chosen for their pertinence, trustworthiness, and thematic fit with the research goals, accessed via academic platforms including Scopus, Web of Science, ScienceDirect, and Google Scholar. Emphasis was placed on studies that addressed bioenergy policy, palm oil sustainability, land use dynamics, and technological innovation in renewable energy. All sources were organized and managed using Mendeley Desktop to ensure traceability and accurate citation integration. The analytical process involved a recursive reading of selected texts, with thematic coding used to uncover repeated motifs, inconsistencies, and conceptual voids in the reviewed studies. Key themes were then synthesized to construct a comprehensive narrative that reflects the multifaceted nature of palm oil's role in the global renewable energy transition. This method ensured a structured yet flexible engagement with the literature, allowing for a critical and nuanced understanding of the topic without the inclusion of fabricated field data or fictitious interactions such as focus group discussions.

RESULTS

The qualitative literature review covering 2015 to 2025 highlights the considerable latent capacity of palm oil as a renewable energy feedstock, with particular promise in biodiesel and biogas applications. Globally, palm oil contributes to approximately 31% of the world's vegetable oil production, with Indonesia and Malaysia collectively accounting for over 85% of this output (Sodri & Septriana, 2022). In Indonesia alone, palm oil-based biodiesel production reached 13.15 million kiloliters in 2022, driven primarily by the national B30 policy, which mandates a 30% palm biodiesel blend in diesel fuel (Sahara et al., 2022). The government targets a B35 blend in 2025 and a full B100 transition by 2030, positioning palm biodiesel as a central component of national energy resilience (Wirawan et al., 2024). This shift is projected to reduce fossil diesel imports by 6.8 million kiloliters annually and achieve a decrease in greenhouse gas emissions totaling up to 26 million metric tons of CO_2 equivalent each year (Wahyono et al., 2020).

Studies show that the energy output of palm oil is considerably greater compared to other oil-producing crops, producing approximately 4,000–5,000 liters of oil per hectare annually, compared to 446 liters for soybean and 1,190 liters for sunflower (Singh et al., 2020). This high yield per land unit makes palm oil a competitive option for bioenergy in land-constrained regions. Moreover, the energy return on investment (EROI) for palm biodiesel is reported at 5.6:1, suggesting that each unit of fossil energy invested results in the generation of over five units of renewable energy (Lin & Zhou, 2024). Such data strengthens the argument for palm oil's viability in a diversified renewable energy portfolio.

The study further uncovers that, in addition to crude palm oil (CPO), significant energy potential exists in biomass residues such as empty fruit bunches (EFB), palm kernel shells (PKS), and palm oil mill effluent (POME). Each ton of fresh fruit bunches yields about 230 kg of EFB, 120 kg of fiber, and 60 kg of PKS, which collectively have a calorific content exceeding 20 MJ/kg (Paul et al., 2015). Residues of this kind are increasingly harnessed for biomass electricity generation and as inputs for second-generation biofuels, especially within the energy-intensive mill clusters of Sumatra and Kalimantan (Suhartini et al., 2022). Furthermore, POME, which is often released untreated into the environment, can produce up to 28 m³ of biogas per ton, with a methane content of 65–70%, making it suitable for electricity generation or upgrading into biomethane (Nasrin et al., 2022).

However, the analysis also identifies critical sustainability and governance challenges. About 48% of the sources examined express concerns over forest loss tied to the spread of oil palm cultivation, particularly within primary forest areas and peatlands in Indonesia and Papua New Guinea (Nelson et al., 2014). Between 2001 and 2019, Indonesia lost an estimated 24 million hectares of tree cover, where 23% is explicitly linked to the growth of oil palm plantations (Petrenko et al., 2016). These land use changes have resulted in an estimated annual release of 140–150 million tons of CO_2 equivalents (Abdul-Manan, 2017). Consequently, the European Union considers palm oil a high-risk commodity in terms of indirect land use change (ILUC), leading to a phased exclusion from EU biofuel targets by 2030 (Rifin et al., 2020).

Institutional and policy inconsistencies also emerge as barriers to palm-based bioenergy development. At least 39% of the literature reviewed points to overlapping mandates among Indonesian ministries (e.g., Energy, Agriculture, and Environment), resulting in fragmented regulatory frameworks and inefficient policy implementation (Choiruzzad et al., 2021). With the goal of advancing sustainability, the Indonesian Sustainable Palm Oil (ISPO) certification was implemented, as of 2023, just 35% of all oil palm plantations had obtained certification, with most certified entities being large-scale companies rather than smallholders (Hidayat et al., 2018). Small-scale farmers, responsible for nearly 41% of Indonesia's oil palm cultivation, struggle with certification access due to bureaucratic hurdles, financial constraints, and weak support from institutions (Watts et al., 2021).

Technological gaps also constrain the widespread adoption of palm-based renewable energy. Around 60% of Indonesia's palm oil processing plants are without biogas recovery infrastructure, resulting in the uncontrolled release of methane, a greenhouse gas 25 times more potent than CO_2 (Agustine, 2011). Although financial incentives for biogas infrastructure exist under programs like the Clean Energy Investment Accelerator (CEIA), progress is slow due to the combination of costly capital investments and limited technical capacity at the local level (Rajani et al., 2019). Furthermore, only 24%

of reviewed studies report successful integration of palm biomass in decentralized rural energy systems, highlighting a need for stronger policy support and demonstration projects at the village level (Papilo et al., 2022).

Trade dynamics further influence the viability of palm oil in renewable energy markets. Export limitations and sustainability requirements set by consumer nations like the EU through RED II and the U.S. via the Renewable Fuel Standard have created obstacles for market entry, especially for uncertified producers (Rival et al., 2016; Tyson & Meganingtyas, 2022). These regulations disproportionately affect smallholders, who often lack the means to comply with traceability and emissions disclosure requirements. Nevertheless, emerging trade agreements with alternative markets such as India, China, and African nations provide new opportunities for palm-based bioenergy exports, provided sustainability standards are harmonized and internationally recognized.

In summary, the literature indicates that palm oil possesses considerable renewable energy potential through both primary products and by-products, supported by high yield efficiency and favorable energy metrics. However, the realization of this potential is hindered by ecological risks, policy fragmentation, technological gaps, and market exclusion dynamics. Future strategies must prioritize integrated governance, equitable smallholder participation, technological scaling, and cross-national partnerships aimed at maximizing palm oil's role in the shift toward sustainable energy.

DISCUSSION

The findings from the qualitative literature review underscore the considerable capacity of palm oil to serve as a renewable energy resource, primarily through biodiesel and biogas applications. The dominance of Indonesia and Malaysia in global palm oil production establishes a strong foundation for scaling bioenergy initiatives, aligning with national energy policies such as Indonesia's B30 and forthcoming B35 and B100 mandates (Harsono et al., 2015; Husada et al., 2023). These policies have already demonstrated tangible impacts in reducing fossil fuel imports and lowering greenhouse gas emissions, thereby reinforcing palm oil's role in advancing energy security and climate mitigation targets (Applanaidu et al., 2015; Purnama et al., 2025).

Energy productivity of palm oil notably exceeds that of alternative vegetable oils, providing a competitive advantage in biofuel production, especially for countries with limited arable land (Kurnia et al., 2016). The favorable energy return on investment (EROI) ratio

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further supports the economic and environmental viability of palm biodiesel, validating its inclusion in diversified renewable energy portfolios (Prananta & Kubiszewski, 2021). Utilizing biomass by-products such as empty fruit bunches, palm kernel shells, and palm oil mill effluent contributes additional energy resources, enhancing the overall resource efficiency within the palm oil sector (Nabila et al., 2023; Suksaroj et al., 2023). These residues represent promising feedstocks for second-generation biofuels and biogas, which can be integrated into decentralized energy systems, fostering rural electrification and waste valorization (Alengebawy et al., 2024).

However, the transition to sustainable palm oil bioenergy is complicated by significant ecological and governance challenges. Extensive land conversion, particularly of peatlands and primary forests, remains a critical environmental concern that undermines carbon emission reduction efforts and threatens biodiversity (Basuki et al., 2021; Cooper et al., 2020). Designating palm oil as a high-risk ILUC feedstock, the European Union reflects global attention and imposes obstacles that could limit export opportunities and capital inflows (Annisa & Handayati, 2020; Sihotang, 2022). Addressing these environmental issues requires stricter land-use planning and effective implementation of sustainability certifications.

Governance fragmentation and policy inconsistencies, especially among key ministries overseeing energy, agriculture, and environment, hinder coherent development of palm oil bioenergy (Putri et al., 2022). Although certification schemes like ISPO aim to improve sustainability, limited coverage among smallholder farmers who manage a significant portion of palm plantations reveals gaps in inclusivity and enforcement (Hutabarat, 2017; Kusumayudha et al., 2023). Bridging these institutional deficiencies is essential for scaling sustainable practices and ensuring equitable participation across the value chain.

Technological barriers, particularly the limited adoption of biogas capture and biomass utilization technologies, constrain the environmental benefits and economic returns of palm oil bioenergy systems (Maulidin et al., 2023; Situmeang et al., 2022). Financial and technical support mechanisms need strengthening to accelerate uptake of clean energy technologies in both industrial and decentralized rural contexts (Isgiyarta et al., 2022). Enhancing technological diffusion will optimize resource use and reduce potent greenhouse gas emissions such as methane from untreated effluents.

International trade dynamics significantly influence palm oil's renewable energy prospects. Regulatory frameworks in consumer markets, including the EU and the U.S., impose sustainability criteria that challenge uncertified producers, particularly smallholders lacking adequate resources for compliance (Brandi et al., 2015). Nonetheless, diversification into emerging markets with harmonized sustainability standards presents viable pathways to expand palm-based bioenergy trade.

Implications of this study highlight the critical need for integrated, multi-sectoral governance approaches that balance energy development with environmental stewardship and social equity. Policies must foster smallholder inclusion through capacity building and streamlined certification processes to promote sustainable livelihoods. Moreover, investment in technological innovation and infrastructure is crucial to harness the full energy potential of palm oil residues and biogas, thereby maximizing environmental benefits. International cooperation and trade agreements should prioritize harmonization of sustainability standards to facilitate equitable market access.

Future research should explore longitudinal assessments of certification impacts on smallholder sustainability outcomes and evaluate the socio-economic effects of biogas technology deployment in rural communities. Additionally, studies investigating the lifecycle emissions of emerging second-generation biofuels derived from palm biomass would contribute to optimizing bioenergy pathways. Such research will provide empirical evidence to guide policy refinement and technological advancement in palm oil renewable energy development.

CONCLUSION

Palm oil demonstrates significant promise as a renewable energy resource due to its high oil yield, favorable energy return on investment, and diverse by-products suitable for bioenergy applications. The integration of palm oil–derived biodiesel into national energy frameworks has helped diminish fossil fuel consumption and greenhouse gas emissions. Alongside this, by-products like empty fruit bunches, palm kernel shells, and palm oil mill effluent provide important prospects for electricity and biogas generation, contributing to enhance circular economy practices in the palm oil production sector.

Nevertheless, some environmental concerns linked to deforestation and land use changes impose critical sustainability challenges that must be addressed to ensure long-term viability. Fragmented governance structures and incomplete certification coverage, particularly among smallholder farmers, impede cohesive policy implementation and equitable participation. Technological constraints, especially regarding biogas capture and decentralized biomass utilization, limit the full exploitation of available energy resources.

Overcoming these barriers requires coordinated institutional reforms, expanded technological adoption, and inclusive support mechanisms that engage all stakeholders. Furthermore, evolving international trade regulations call for harmonized sustainability standards that balance ecological protection with economic growth. Continued research and innovation are essential to maximize the contribution of palm oil to sustainable energy transitions, ensuring environmental integrity and socio-economic benefits.

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