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Exploring the Relationship Between Palm Oil and Bioenergy

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ABSTRACT

The global pursuit of renewable energy has intensified interest in palm oil as a key bioenergy feedstock, particularly in biodiesel production. This study explores the evolving relationship between palm oil and bioenergy through a bibliometric analysis of scientific publications indexed in the Scopus database. Using VOSviewer for data visualization, we examined keyword co-occurrence, temporal trends, thematic density, author collaboration networks, and institutional and country-level partnerships. The results reveal that research has transitioned from foundational topics such as greenhouse gas emissions and biodiesel to more advanced themes like anaerobic digestion, waste valorization, and biotechnological innovations. Malaysia and Indonesia emerged as leading contributors, both in publication volume and international collaboration, while emerging economies such as Brazil and Thailand show increasing engagement. The study provides practical insights for policymakers, industry stakeholders, and researchers by mapping knowledge clusters and highlighting research gaps. It also contributes theoretically by integrating environmental, technological, and socio-political perspectives on palm oil-based bioenergy systems. Limitations include database constraints and the exclusion of non-English literature. Overall, this study offers a timely and comprehensive overview of how palm oil is positioned within global bioenergy discourses and provides a foundation for more sustainable and inclusive energy transitions.

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1. INTRODUCTION

In the era of global climate change and escalating energy demands, the search for sustainable and renewable sources of energy has become more urgent than ever [1], [2]. Among the array of bio-based energy alternatives, palm oil has emerged as a significant player, particularly in countries with tropical climates such as Indonesia, Malaysia, Thailand, and parts of Africa and Latin America. As the world transitions away from fossil fuels, palm oil offers the potential to provide an efficient, scalable, and renewable feedstock for bioenergy, including biodiesel production. This opportunity positions palm oil at the center of sustainability debates that intertwine environmental conservation, energy security, and economic development [3].

Palm oil's rise in the global bioenergy sector is not without controversy. While its high yield per hectare and efficient processing have been celebrated, the expansion of oil palm plantations has raised serious environmental concerns [4], [5]. Issues such as deforestation, biodiversity loss, carbon emissions from land-use changes, and social conflicts have placed the palm oil industry under intense international scrutiny. However, it is also crucial to recognize that palm oil represents a vital economic lifeline for millions of smallholder farmers, particularly in Southeast Asia, and serves as a strategic commodity in national energy and agricultural policies [6].

Bioenergy derived from palm oil (primarily in the form of biodiesel) has been adopted by several countries as part of their renewable energy mix and climate action strategies [7]. Indonesia and Malaysia, in particular, have implemented mandatory biodiesel blending programs (such as B30 and B20) to reduce dependency on imported fossil fuels, manage palm oil surpluses, and cut greenhouse gas emissions. These policies have created a unique nexus between agricultural production and energy transformation, positioning palm oil not just as a food commodity, but also as a pillar of national energy infrastructure [8], [9].

Nevertheless, the relationship between palm oil and bioenergy is complex and dynamic, shaped by multiple factors including international trade, environmental regulations, technological innovation, and political economy [10]. The volatility of palm oil prices, the influence of global sustainability standards (such as RSPO and ISCC), and the shifting preferences of major markets (e.g., the EU's Renewable Energy Directive) continuously affect the viability and perception of palm-based bioenergy [11], [12]. Moreover, emerging bioenergy technologies and feedstocks such as algae, jatropha, and cellulosic biomass raise critical questions about the long-term role of palm oil in the renewable energy transition.

Despite a growing body of literature on biofuels and palm oil, there remains a lack of comprehensive, interdisciplinary understanding of how palm oil fits within the evolving bioenergy landscape. Most studies tend to focus either on the agronomic or environmental implications of palm cultivation, or on the techno-economic feasibility of biodiesel production. Few integrate both dimensions while also considering the broader socio-political, ecological, and market-driven dynamics at play. This gap in knowledge calls for a more holistic inquiry into the multifaceted relationship between palm oil and bioenergy.

The development of palm oil-based bioenergy presents both opportunities and challenges. While it offers a pathway toward renewable energy generation and rural economic empowerment, it also raises significant concerns regarding environmental degradation, food security trade-offs, and compliance with global sustainability benchmarks. The problem lies in the lack of integrative understanding of how palm oil interacts with the global bioenergy system in terms of production, policy, trade, and ecological impact. Without a nuanced and evidence-based analysis, efforts to promote palm oil as a bioenergy source may risk reinforcing unsustainable practices or undermining broader climate goals. This study aims to explore the relationship between palm oil and bioenergy through a comprehensive review of the literature and analysis of key trends, challenges, and opportunities.

2. METHODS

This study adopts a bibliometric and integrative literature review approach to explore the complex relationship between palm oil and bioenergy. The bibliometric analysis was conducted using publications retrieved from the Scopus database, which is recognized for its extensive coverage of peer-reviewed scientific literature. The search strategy involved using specific keywords such as *"palm oil," "bioenergy," "biodiesel," "renewable energy,"* and *"sustainability,"* with filters applied to limit the search to articles published between 2000 and 2025. The inclusion criteria ensured the selection of relevant articles from reputable journals in the fields of environmental science, energy policy, agricultural economics, and sustainability studies.

To conduct the bibliometric mapping, the software VOSviewer was used to visualize co-authorship networks, keyword co-occurrence, and citation patterns. This technique enables the identification of influential authors, thematic clusters, and research trends within the domain. Network visualization helped to trace how scholarly interest in the palm oil–bioenergy nexus has evolved over time, which regions are most active in publishing research on this topic, and how keywords have shifted to reflect emerging challenges and innovations (e.g., sustainability certification, life cycle analysis, land-use change). The results of the bibliometric mapping served as a foundation for deeper thematic exploration.

Following the bibliometric stage, an integrative thematic analysis was performed on the most highly cited and thematically relevant papers. These selected studies were reviewed qualitatively to identify key dimensions such as policy frameworks, environmental trade-offs, technological innovations, and socio-economic impacts related to palm oil-based bioenergy.

3. RESULTS AND DISCUSSION

3.1 Keyword Co-Occurrence Network

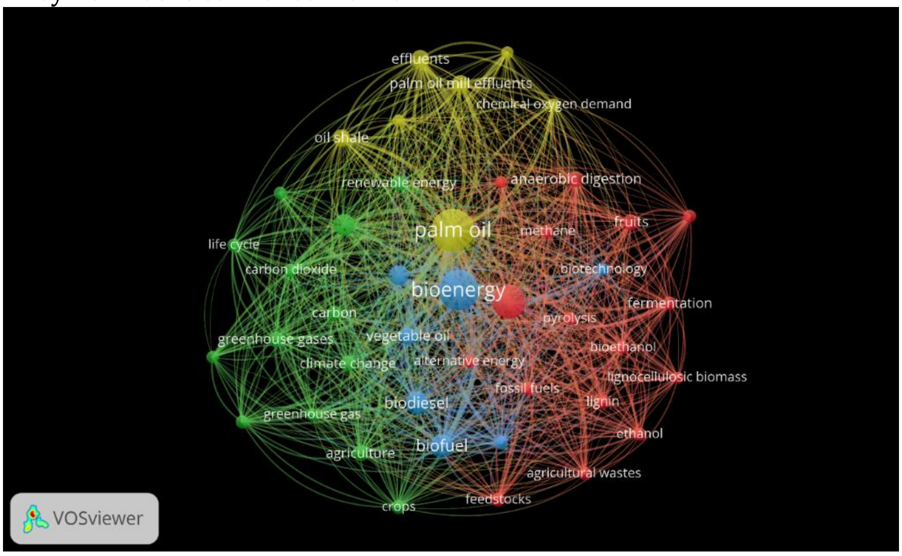

Figure 1. Network Visualization

Source: Data Analysis Result, 2025

The visualization clearly shows "palm oil" and "bioenergy" as the two most central and co-occurring keywords, indicated by their large node sizes and central positions. These keywords form the thematic backbone of the research domain. Their prominence signifies that most publications explore the interconnectedness of palm oil production and its applications in the bioenergy sector, especially in the context of sustainability, fuel alternatives, and agricultural transformation. Their proximity also indicates a strong semantic relationship, meaning they are frequently discussed together in the same studies.

The network is organized into four main clusters, each color-coded to represent distinct but interlinked research themes:

1. Green Cluster (bottom-left): Focused on environmental implications such as greenhouse gases, carbon dioxide, climate change, and life cycle. This cluster reflects research exploring the ecological impact of palm oil-based bioenergy and its role in emissions reduction or contributions to climate change.
2. Blue Cluster (bottom-center): Encompasses terms like

biodiesel, biofuel, vegetable oil, and alternative energy. This signifies technological and economic discussions surrounding the use of palm oil as a fuel feedstock, production processes, and alternatives to fossil fuels.

3. Red Cluster (right side): Contains terms such as biotechnology, fermentation, pyrolysis, lignin, and ethanol. This cluster reflects innovation and process engineering, including biochemical and thermochemical conversions of palm oil and its residues into various forms of bioenergy.
4. Yellow Cluster (top): Includes palm oil mill effluents, chemical oxygen demand, and anaerobic digestion, highlighting research on waste management, environmental impacts of byproducts, and wastewater treatment from palm oil processing.

The strong interconnections in the green cluster emphasize the environmental trade-offs in using palm oil for energy purposes. Keywords like greenhouse gas, carbon, and life cycle suggest the prominence of Life Cycle Assessment (LCA) studies evaluating carbon footprints and emissions across the supply chain. These insights are crucial in policy discussions on the sustainability of palm-based biofuels and help determine compliance with global regulations like the EU Renewable Energy Directive (RED II).

The red cluster showcases how palm oil is not only used directly for biodiesel but also serves as a substrate in advanced biotechnological pathways. Keywords like *biotechnology*, *bioethanol*, *pyrolysis*, and *agricultural wastes* suggest a growing trend in valorizing waste biomass (e.g., empty fruit bunches, palm kernel shells) for second-generation biofuels. The presence of *fermentation*, *methane*, and *anaerobic digestion* also signals expanding research into biogas production, closing the loop of resource use and enhancing the circular economy aspect of palm oil value chains.

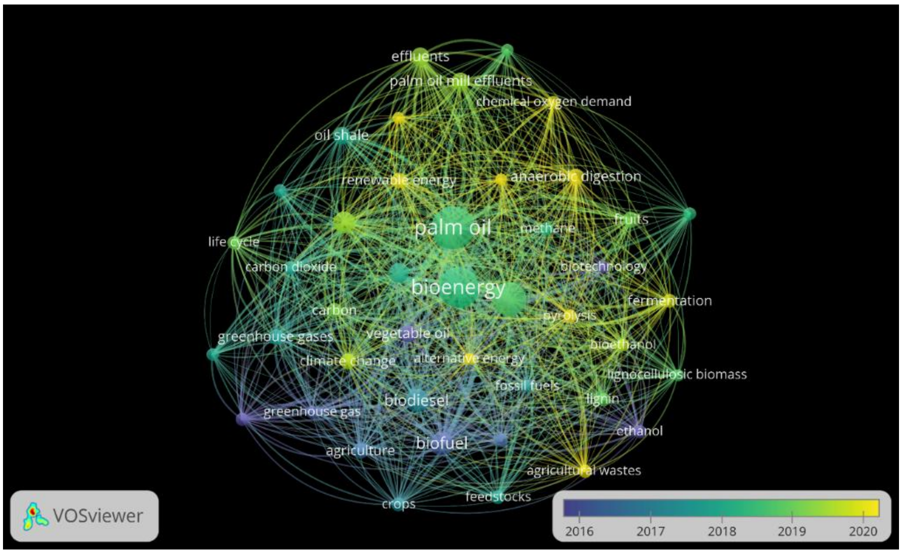

Figure 2. Overlay Visualization
Source: Data Analysis Result, 2025

The overlay visualization shows a clear temporal gradient in keyword usage, with colors ranging from dark blue (older publications, ~2016) to bright yellow (more recent, ~2020). Central terms such as *"palm oil"* and *"bioenergy"* appear in light green, indicating sustained research interest across multiple years, with a peak between 2017 and

2019. This suggests that these two topics have served as the thematic core of the field and continue to attract scholarly attention. Keywords colored in yellow, such as *"renewable energy," "anaerobic digestion," "biotechnology,"* and *"methane,"* represent more recent areas of interest, typically post-2019. These topics reflect a shift toward waste-to-energy conversion, biochemical innovations, and environmental sustainability within the palm oil–bioenergy nexus. Additionally, *"palm oil mill effluents"* and *"chemical oxygen demand"* also appear in yellow, suggesting growing concerns around the environmental impacts of palm oil production and increasing interest in circular economy solutions like energy recovery from waste streams. Terms displayed in dark blue and purple, such as *"biodiesel," "biofuel," "greenhouse gas,"* and *"climate change,"* were heavily featured in earlier literature (2016–2017). These reflect foundational research that framed palm oil as a source of first-generation biofuels and evaluated its implications for emissions and sustainability. While still relevant, their earlier positioning suggests that research has evolved from basic fuel applications to more advanced technologies, byproduct utilization, and integrated energy systems.

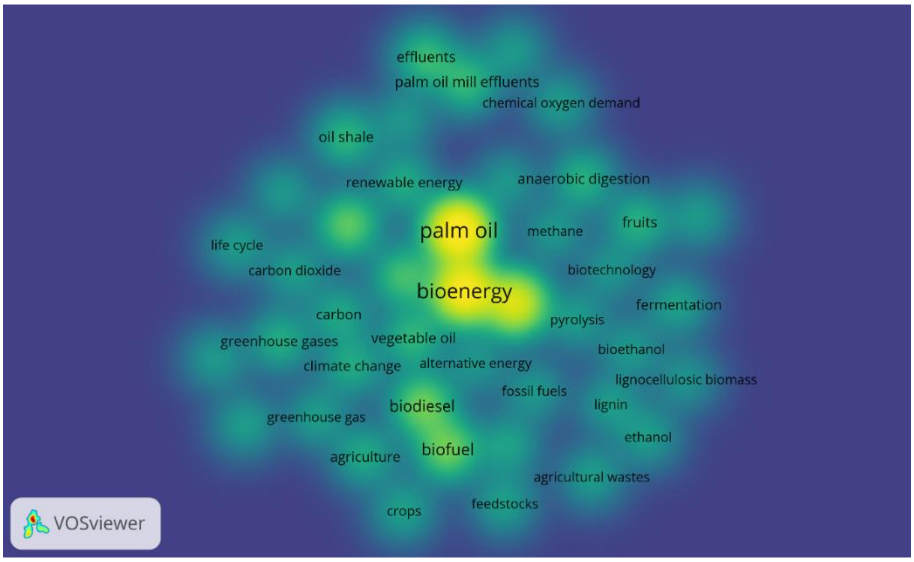

Figure 3. Density Visualization

Source: Data Analysis, 2025

The density map highlights "palm oil" and "bioenergy" as the two most intensively studied and co-occurring terms, indicated by their bright yellow color at the center of the visualization. This suggests that these keywords are central to the scholarly discourse and appear with high frequency across publications. Closely related concepts such as "biodiesel," "biofuel," "renewable energy," and "greenhouse gases" also show relatively high density (green to yellow), reflecting their importance in discussions on the role of palm oil as a renewable energy source and its environmental impacts. These terms form the thematic core of the field, especially in relation to energy transition and climate change mitigation. In contrast, surrounding terms such as "biotechnology," "anaerobic digestion," "lignocellulosic biomass," and "chemical oxygen demand" appear in green or blue zones, indicating that while these topics are present in the literature, they are less frequently discussed. This pattern suggests that areas such as biotechnological innovation, waste utilization, and advanced conversion technologies are emerging or niche subfields within the broader palm oil–bioenergy research landscape.

3.2 Co-Authorship Network

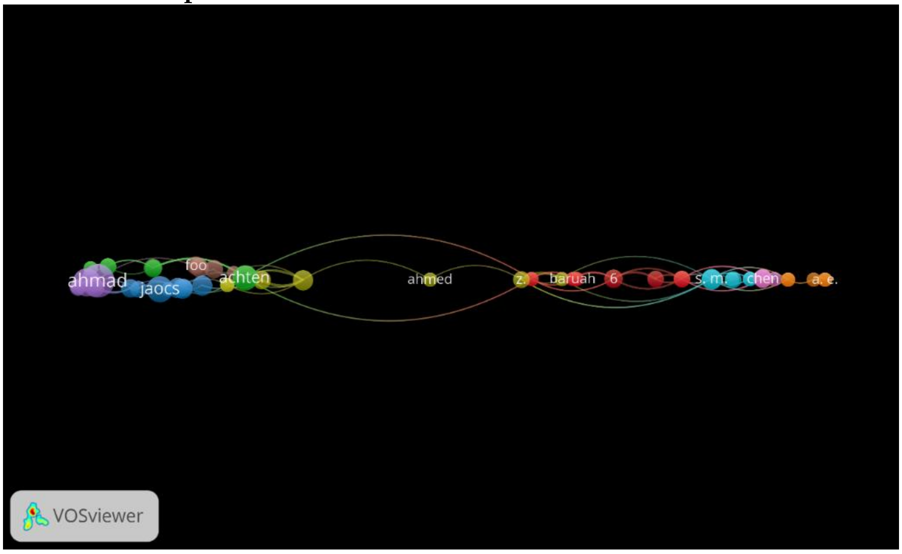

Figure 4. Author Collaboration Visualization

Source: Data Analysis, 2025

Figure 4 presents a co-authorship network that maps collaborative relationships among authors in the research domain of palm oil and bioenergy. The nodes represent individual authors, while the links between them indicate co-authored publications. The network reveals several distinct clusters, each colored differently, suggesting tight-knit author groups who collaborate frequently within their own circles. Notably, authors like Ahmad, Achten, Chen, and Baruah appear more central, serving as bridging nodes that connect multiple clusters—suggesting they play key roles in knowledge dissemination across collaborative networks.

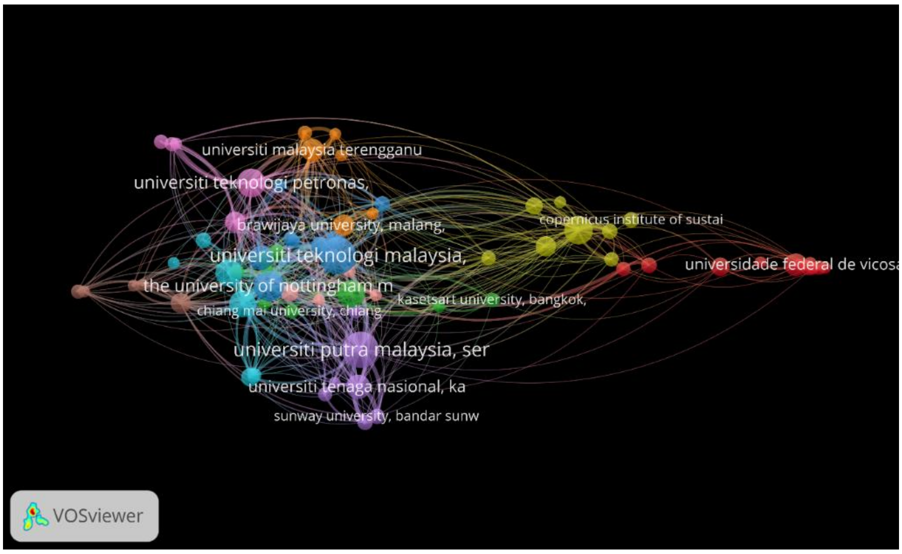

Figure 5. Affiliation Collaboration Visualization

Source: Data Analysis, 2025

Figure 5 shows a co-authorship network among institutions in the field of palm oil and bioenergy research. The size of the nodes indicates the number of publications or collaborative links, while the colors represent clusters of institutions that frequently collaborate. Prominent institutions such as Universiti Teknologi Malaysia, Universiti Putra Malaysia, and The University of Nottingham Malaysia are at the center of the network, highlighting Malaysia's dominant role and strong internal collaboration in this research area. Meanwhile, institutions like Universidade Federal de Viçosa (Brazil) and Copernicus Institute of Sustainable Development (Netherlands) form more peripheral clusters, suggesting strong national or regional collaboration but fewer cross-continental co-authorships.

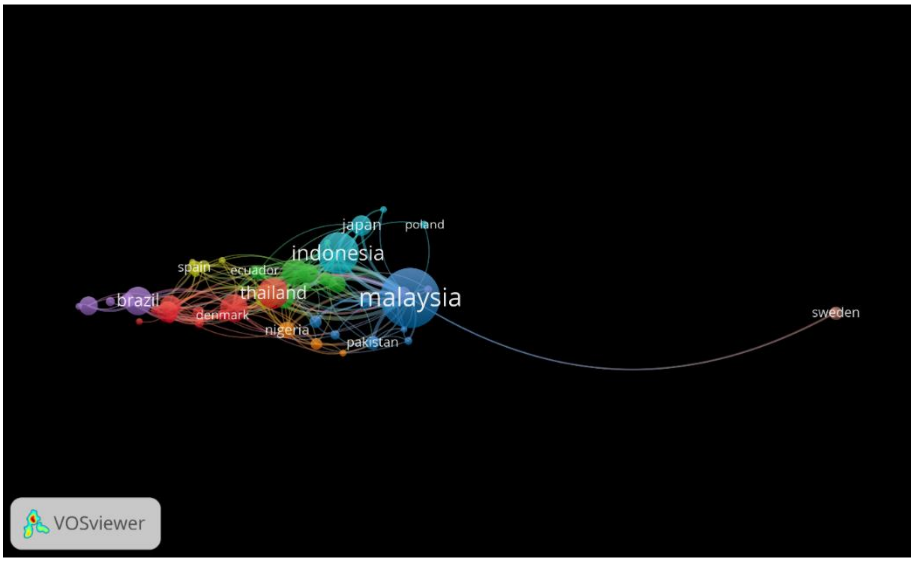

Figure 6. Country Collaboration Visualization

Source: Data Analysis, 2025

Figure 6 illustrates a country-level collaboration network in the research domain of palm oil and bioenergy. The node size indicates the volume of publications or co-authored research, while the connecting lines represent international collaborations. Malaysia emerges as the most dominant hub, with extensive collaborations particularly with Indonesia, Thailand, Japan, Pakistan, and Poland, signifying its central role in driving research and fostering regional partnerships in Southeast Asia. Indonesia also plays a key role, closely connected with Malaysia and other ASEAN and global partners. Countries like Brazil, Spain, and Sweden form smaller, less connected clusters, with Sweden notably isolated, suggesting limited integration with the main collaborative networks.

3.3 Citation Analysis

Table 1. Top Cited Research

Citations	Authors and year	Title
554	[13]	Indirect land-use changes can overcome carbon savings from biofuels in Brazil
458	[14]	Biofuel plantations on forested lands: Double jeopardy for biodiversity and climate | Plantaciones de biocombustible en terrenos boscosos: Doble peligro para la biodiversidad y el clima
301	[15]	Renewable and sustainable bioenergies production from palm oil mill effluent (POME): Win-win strategies toward better environmental protection
250	[16]	Life cycle assessment of palm biodiesel: Revealing facts and benefits for sustainability
235	[17]	Different palm oil production systems for energy purposes and their greenhouse gas implications

Citations	Authors and year	Title
210	[18]	Oil palm economic performance in Malaysia and r&d progress in 2017
210	[19]	Biomass and bioenergy: An overview of the development potential in Turkey and Malaysia
209	[20]	Crop Expansion and Conservation Priorities in Tropical Countries
174	[21]	Thermophilic anaerobic co-digestion of oil palm empty fruit bunches with palm oil mill effluent for efficient biogas production
167	[22]	Biofuel scenarios in a water perspective: The global blue and green water footprint of road transport in 2030

Source: Scopus, 2025

Practical Implication

This study provides practical insights for policymakers, agribusiness stakeholders, and energy planners aiming to integrate palm oil into national and global bioenergy strategies. The bibliometric findings highlight the strategic role of countries like Malaysia and Indonesia in spearheading innovation and collaboration in palm oil-based bioenergy research. This underscores the need for evidence-based regulation, especially concerning land use, emissions, and waste valorization. Moreover, the identification of emerging topics such as anaerobic digestion, biotechnology, and palm oil mill effluents opens pathways for technological innovation and sustainable byproduct management. For industry players, the results can inform investment decisions and R&D directions, particularly toward more sustainable and circular bioenergy systems. Additionally, international collaboration patterns offer guidance for building academic and industrial partnerships, especially between the Global South and Global North.

Theoretical Contribution

The study contributes to the literature by offering a systematic and interdisciplinary synthesis of palm oil's role in the bioenergy landscape through a bibliometric lens. Unlike prior studies that focus narrowly on either environmental or engineering aspects, this research captures the multi-dimensional nature of the field, integrating themes from sustainability science, renewable energy policy, industrial ecology, and tropical agriculture. The co-occurrence and temporal keyword analyses provide a dynamic understanding of how academic discourse has evolved—from biodiesel and climate change toward biotechnological processes and waste-based energy recovery. The study also advances theoretical discourse by emphasizing the interconnectedness of food-energy-environment systems in the Global South, offering a grounded perspective to theories on green transitions, resource governance, and technological adoption in emerging economies.

Limitation

While this study offers valuable insights, several limitations should be acknowledged. First, the bibliometric analysis is limited to the Scopus database, which, while comprehensive, may not capture all relevant publications indexed in Web of Science, Google Scholar, or regional databases. Second, the analysis is constrained by keyword selection, which, although carefully curated, might have excluded literature using alternative terminologies or regional language publications. Third, the study focuses on the co-occurrence and network structure of publications rather than a full content-based critical appraisal of research findings, limiting its capacity to assess methodological quality or empirical robustness. As the bioenergy sector is highly dynamic, policy shifts and technological innovations beyond the publication date may not be fully captured in the current snapshot, suggesting the need for periodic updates and complementary qualitative reviews.

4. CONCLUSION

This study has explored the multifaceted relationship between palm oil and bioenergy through a comprehensive bibliometric analysis, revealing the central role of palm oil in renewable energy discourse, particularly in biodiesel production, waste utilization, and technological innovation. The findings highlight that while palm oil remains a dominant feedstock in the bioenergy sector, research is increasingly shifting toward more sustainable and circular approaches—such as the use of palm oil mill effluents and biotechnological methods. Southeast Asian countries, especially Malaysia and Indonesia, have emerged as key contributors to the global knowledge network, underscoring their strategic importance in both production and research collaboration. However, the study also reveals fragmented international partnerships and uneven topic coverage, pointing to the need for broader global cooperation and integrative, cross-disciplinary frameworks. Moving forward, bridging the gaps between environmental sustainability, technological innovation, and policy integration will be essential to ensure that palm oil contributes effectively and responsibly to the global bioenergy transition.

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