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By Indonesian Oil Palm Society

Oil Palm Plantation Fund Management Agency

Palm oil is Indonesia's most strategic commodity.
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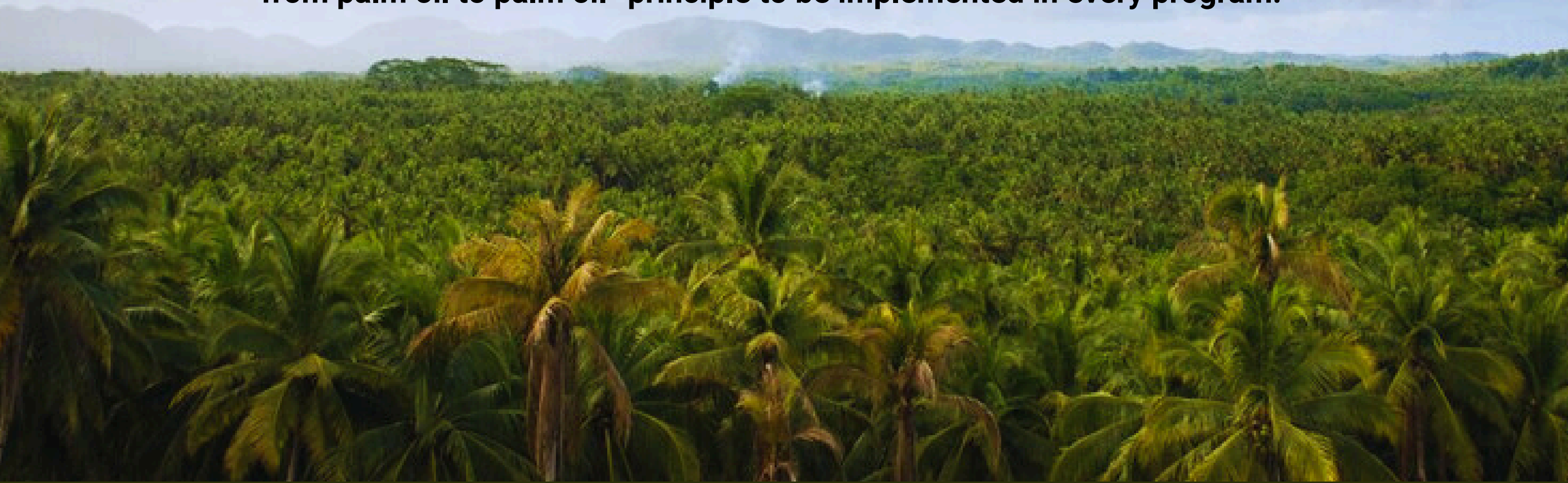

Main Area of Fund Disbursement

(Based on Presidential Regulation No. 61/2015)

- Food Security, Downstream Market Development and Biodiesel Supply
- Replanting
- Facilities, Infrastructures, and Farmers Empowerment
- Human Resources Development
- Research and Development
- Promotion and Advocacy

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Farmers Training and Development
A human resources development program in palm oil sector through training, education, counseling, accompainment and facilitation.

Research and Development
Support the research and development initiatives in palm oil sector to increase productivity, sustainability and product development.

Promotion and Advocacy
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Global Research Trends on Oil Palm Plantation and Deforestation: A Bibliometric Analysis

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ABSTRACT

Palm oil is one of the most efficient and widely consumed vegetable oils globally, but its expansion has been linked to tropical deforestation, biodiversity loss, and land use change. As global environmental concerns intensify, scholarly interest in the palm oil-deforestation nexus has grown rapidly. This study offers an updated science mapping analysis of global research on this topic until 10 July 2025. Drawing on 1,622 peer-reviewed articles retrieved from Scopus and Web of Science, we applied bibliometric analysis and science mapping to examine publication trends, thematic structures, collaboration networks, and the intellectual foundations of the field. Findings reveal a sharp increase in research output since the early 2000s, with Environmental Research Letters, Land Use Policy, and PLoS One emerging as the most relevant sources. The most prolific authors and institutions are primarily based in Europe, North America, and Southeast Asia, with the University of Göttingen and Bogor Agricultural University (IPB University) playing central roles. Indonesia now leads in single-country publications, reflecting its growing research capacity and strategic importance in the global palm oil landscape. The existing literature is predominantly framed through ecological and technical lenses, focusing on biodiversity, emissions, and sustainability certification. Keyword and co-citation analyses show emerging themes such as ‘spatial analysis’, ‘machine learning’, and expanding regional focus beyond Southeast Asia. However, critical gaps remain, particularly around social justice, land rights, and indigenous knowledge. This study highlights the need for more inclusive and interdisciplinary research approaches that foreground power dynamics, local voices, and alternative knowledge systems. Additionally, as a major producer and increasingly active research contributor, Indonesia holds strong potential to be a focus in future research agendas. The study provides a strategic foundation for researchers, funders, and policymakers engaged in sustainability and land-use governance.

Keywords: Deforestation, Indonesia, international collaboration, palm oil, scientific research

INTRODUCTION

Palm oil has emerged as one of the most contested commodities in the global sustainability landscape because palm oil is the world’s most widely consumed vegetable oil (Corley 2009; Hansen *et al.* 2015). However, palm oil is also widely associated with deforestation and land use change in the tropics, particularly in Southeast Asia (Vijay *et al.* 2016; Wicke *et al.* 2011). Palm oil rapid expansion has been strongly linked to forest loss, biodiversity

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decline, and increased carbon emissions, making it a center of sustainability debates and regulatory interventions (Meijaard *et al.* 2020). The environmental and social complexities of palm oil-driven deforestation have drawn increasing attention from scientists, policymakers, and civil society actors alike (Lyons-White & Knight 2018).

As environmental and governance concerns have intensified, scholarly interest in the palm oil and deforestation nexus has grown substantially (Dauvergne 1993; Teng *et al.* 2020). Over the past two decades, research on this topic has expanded across disciplines ranging from remote sensing and ecology to political science, development studies, and environmental governance (Hansen *et al.* 2015). The literature reflects technical concerns, emissions measurement, land cover mapping, and socio-political issues involving land rights, policy instruments, and corporate accountability (Berenschot *et al.* 2024; Choiruzzad *et al.* 2021; Varkkey *et al.* 2018). Despite this rapid growth, the literature remains fragmented, and there is a lack of systematic synthesis to understand its structure, key themes, and evolving patterns.

Bibliometric analysis offers a robust set of tools to address this gap, allowing for a quantitative overview of the scientific landscape, revealing publication trends, collaborative networks, and emerging research fronts that are not captured through narrative reviews (Donthu *et al.* 2021; Kumar 2025). While foundational bibliometric work has been done by Aleixandre-Benavent *et al.* (2018) on global deforestation research, this lens has not yet analyzed commodity-specific drivers, particularly on palm oil.

Few global studies have systematically mapped the structure of palm oil, but not always linked to deforestation research, using a quantitative method like bibliometric analysis (Fischer *et al.* 2020; Mba *et al.* 2015; Tucker Lima *et al.* 2017). Existing reviews are often qualitative or geographically focused, such as those emphasizing regions like Southeast Asia (Afriyanti *et al.* 2016; Cisneros *et al.* 2021; Mukherjee & Sovacool 2014) and the Amazon (Kuss *et al.* 2015; Vijay *et al.* 2018), leaving important questions unanswered about broader collaboration patterns, thematic development, and research influence. Moreover, social, political, and economic dimensions, previously flagged as underrepresented by Aleixandre-Benavent *et al.* (2018), may be similarly neglected in the palm oil literature.

This paper aims to map and analyze the global scientific literature on palm oil and deforestation using bibliometric analysis. Specifically, it seeks to answer the following research questions (RQs); What are the key trends and thematic clusters in global research on palm oil and deforestation? How are countries and institutions collaborating in this study area, and which are most influential? What gaps, shifts, or emerging narratives can be observed in the palm oil and deforestation literature?

This paper contributes to ongoing developments in bibliometric scholarship and knowledge mapping by applying a commodity-specific lens to the deforestation research landscape. It also offers timely insights for international policy debates, such as those surrounding the EU Deforestation Regulation (EUDR), by identifying dominant narratives, key actors, and knowledge gaps. It provides a strategic foundation for researchers, funders, and policymakers seeking to engage with and shape the evolving field of palm oil and deforestation research.

MATERIALS AND METHODS

Data Collection and Methods

This paper employed a bibliometric analysis of the global research landscape on palm oil and deforestation. Bibliographic data were retrieved from two widely recognized databases, Scopus and Web of Science (WOS), which are frequently used in bibliometric studies (Berniak-Woźny & Wejsis-Gołębiak 2023; Fahimnia *et al.* 2015) due to their extensive coverage of peer-reviewed scientific literature and compatibility with analytical tools. A Boolean search string was developed to identify relevant publications at the intersection of palm oil and deforestation. The search query used was: (“palm oil” OR “oil palm” OR elais) AND (deforest* OR “forest loss” OR “land use change” OR “forest degradation” OR “forest clearing” OR “forest conversion” OR “tropical deforestation”).

This query was applied to the Title, Abstract, and Keywords fields in Scopus and Topic in WOS, to ensure the relevance of retrieved articles while capturing diverse terminologies used in the literature. The search was conducted on 10 July 2025. Only peer-reviewed articles published in journals and marked as final publication stage were included to ensure quality and consistency. All selected records were written in English, with no restriction on the year of publication to allow for a comprehensive temporal analysis.

A total of 1,250 articles were retrieved from Scopus and 1,329 from WOS. 957 duplicated entries across databases were identified and removed using combinations of author, year, article title, and journal metadata, performed in both RStudio and EndNote. A set of 1,622 articles was obtained as final data for further analysis. The bibliographic data from Scopus and WOS were exported in .bib and .ris formats, combined, and processed using two key tools: First is Bibliometrix, an R-tool for comprehensive science mapping analysis (Aria & Cuccurullo 2017).

Second is VOSviewer, a software that visualizing bibliometric networks (Moral-Muñoz *et al.* 2020). A thesaurus method was applied to clean and standardize the keywords, merge synonymous terms, like palm oil and oil palm, land use change vs land-use change, and harmonize author and institutional names to ensure accuracy in collaboration and co-citation mapping.

Data Analysis

The analysis was structured to address three guiding research questions related to trends, collaboration patterns, and thematic evolution in global research on palm oil and deforestation. A combination of quantitative bibliometric analysis and science mapping methods was employed to explore the structure and development of the field. To address RQ1, we conducted a descriptive bibliometric analysis and keyword co-occurrence analysis. Descriptive indicators included annual publication volume, most prolific journals, authors, and institutions. Keyword analysis was performed using the co-occurrence function in VOSviewer, based on author keywords and keywords plus. The resulting network maps were clustered by modularity, allowing us to identify major research themes and observe the emergence or decline of specific topics over time. Term frequency and temporal overlays were used to detect trending or emerging concepts in recent years.

To answer RQ2, we carried out co-authorship network analysis at the levels of countries, institutions, and individual authors. VOSviewer was used to visualize international collaboration patterns and assess the density and centrality of key actors. Country collaboration networks were analyzed to highlight North–South and South–South research dynamics. We also calculated citation-based indicators such as total citations and average citations per publication to assess influence. For RQ3, we triangulated insights from the keyword evolution analysis, co-citation mapping, and collaboration patterns. Co-citation analysis revealed the intellectual foundations of the field, identifying clusters of frequently co-cited references. This allowed us to assess which bodies of literature are most influential and whether certain perspec-tives, such as those related to justice, governance, or socio-political dynamics, are underrepresented. Temporal mapping of keywords and co-authorship trends further supported our interpretation of evolving narratives and research gaps.

Limitations

While this study offers a comprehensive bibliometric analysis of global palm oil and deforestation research, several limitations should be acknowledged. First, the analysis was limited to peer-reviewed articles indexed in Scopus and WOS. Although these databases provide broad and reputable coverage, they may exclude relevant publications from other sources such as Google Scholar, regional databases, or non-English journals. This constraint could lead to the under-representation of Global South scholarship, particularly research published in local languages or national journals from palm oil-producing countries such as Indonesia and Malaysia.

Second, the dataset was restricted to articles published in English and excluded other forms of knowledge production, such as books, policy reports, conference proceedings, and dissertations. These types of documents often contain early-stage insights or practitioner-based knowledge that are not always captured in journal publications. As such, the analysis may lean toward academically established voices and overlook important alternative perspectives.

Third, bibliometric analysis is inherently metadata-driven, relying on titles, abstracts, keywords, and citation relationships. While powerful for identifying patterns and structures, these methods cannot fully capture the nuanced arguments, contextual meanings, or critical perspectives embedded in the full texts of the articles. Consequently, thematic clusters and keyword co-occurrence patterns should be interpreted with caution.

Fourth, using tools such as Bibliometrix and VOSviewer involves several technical constraints, particularly related to threshold settings, clustering algorithms, and the disambiguation of author names and institutional affiliations. Although the analysis used standardized bibliographic formats, combining Scopus and Web of Science datasets, which differ in content despite sharing similar file formats, can present challenges. Specifically, VOSviewer is limited in its ability to analyze merged datasets, restricting outputs to co-authorship and keyword co-occurrence networks, while co-citation analysis cannot be performed on combined data. These limitations may affect network visualizations' accuracy and resolution, especially when dealing with large, heterogeneous datasets.

Finally, citation-based indicators are subject to temporal bias. Recently published articles may not have had sufficient time to accumulate citations, potentially limiting the visibility of emerging research areas or new contributors in the field.

RESULTS AND DISCUSSION

Trends and Thematic Clusters in Palm Oil and Deforestation Research

A total of 1,622 peer-reviewed journal articles were included in this bibliometric analysis. As shown in Figure 1, the annual number of publications has increased significantly over the past two decades, reflecting growing academic attention to the environmental and socio-political implications of palm oil-driven deforestation. The earliest article identified in the dataset was published in 1980, but publication activity remained minimal until the early 2000s. Since then, a marked acceleration has been observed, particularly after 2005, which aligns with rising global concern over tropical forest loss and the expanding footprint of oil palm plantations.

The field reached its highest output in 2019, with 162 articles published. This peak coincides with intensified policy debates, including zero-deforestation commitments and the rising influence of sustainability certification schemes such as the RSPO. While publication numbers declined slightly after 2020, the overall trend, illustrated by the polynomial trendline in Figure 1, demonstrates sustained scholarly engagement and thematic diversification.

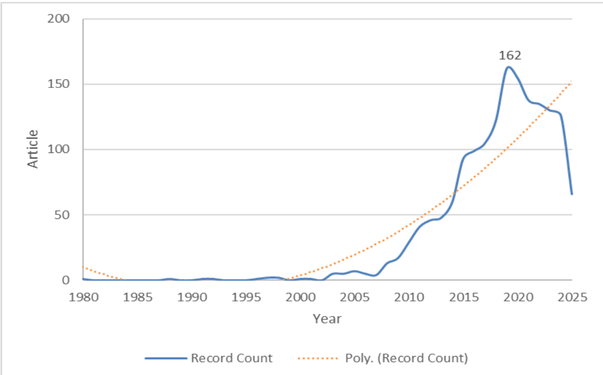

Figure 1 Annual scientific production and publication trends (1980–2025)

The publication landscape on palm oil and deforestation is concentrated in many high-impact, interdisciplinary journal, reflecting environmental, policy, and scientific complexity. The most prolific source was

Environmental Research Letters, based in the United Kingdom, which published 54 articles on this subject, followed closely by Land Use Policy with 46 articles and PLoS One with 42 articles. These journals represent platforms that attract wide-ranging contributions from environmental science, land use studies, and sustainability research.

Table 1 presents the top 10 most relevant journals regarding publication volume. Notably, journals such as Biological Conservation, Conservation Letters, and Forest Policy and Economics show strong disciplinary emphasis on biodiversity, conservation policy, and socio-environmental governance. Despite having fewer articles, some journals demonstrated high influence per publication. For example, Proceedings of the National Academy of Sciences of the United States of America (PNAS) had only 19 relevant articles but recorded a striking 4,523 total citations, resulting in an average of 238.1 citations per article. Similarly, Conservation Letters and Global Change Biology had high citations per article, indicating the enduring impact of select contributions in those journals.

These patterns suggest that while the topic is broadly distributed across environmental journals, a few key outlets serve as intellectual hubs for high-visibility and widely cited research. Open-access platforms (PLoS One) and high-impact, policy-relevant journals, like Global Environmental Change and Journal of Cleaner Production, indicate that palm oil and deforestation research spans technical science and applied policy domains.

Author-level analysis reveals a concentrated group of highly productive researchers who have shaped the development of palm oil and deforestation studies. As shown in Figure 2, the most prolific contributor is Erik Meijaard, with 34 publications, many of which are foundational to the field, particularly in the areas of biodiversity conservation, ecological impacts of oil palm expansion, and sustainable land-use strategies. His work spans empirical ecological research and applied conservation policy, often within Southeast Asia. Following closely are David Edwards, 32 articles, and Stefan Scheu, 30 articles, which have contributed significantly to ecological studies of deforestation and habitat degradation. Other leading authors include Robert Ewers, Benoit Goossens Azhar, Alexander Knohl, and David Gaveau, whose research often combines remote sensing, land-use modeling, and conservation planning. Scholars like Lian Pin Koh and Marc Ancrenaz are also prominent for their work on sustainable palm oil certification, wildlife monitoring, and socio-ecological dynamics within palm-producing regions.

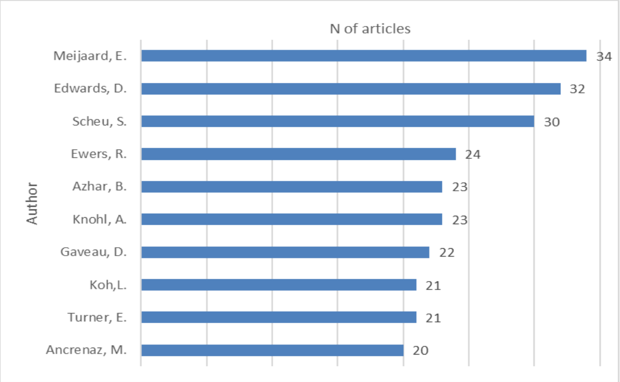

Figure 2 Top 10 most prolific authors

The dominance of these authors underscores the ecological emphasis in the literature, as most of their work is grounded in conservation biology and land system science. While highly cited and influential, this concentration may also reflect the field's reliance on particular institutions and collaborations, raising questions about epistemic diversity and the visibility of Global South researchers.

The keyword analysis offers insights into the conceptual structure and thematic orientation of the oil palm plantation and deforestation research landscape. As shown in Table 2, the most frequently used keywords across the dataset include palm oil (1,056 occurrences), land use change (706), deforestation (644), and oil palm plantation (447). These terms reflect the core environmental issues that underpin much of the literature, emphasizing the role of oil palm plantations as land-intensive agricultural systems that have expanded rapidly across tropical regions, particularly in Southeast Asia.

The term oil palm plantation refers to the crop and its cultivation system, encompassing the spatial and ecological dimensions of large-scale monoculture that are often associated with deforestation, habitat loss, and carbon emissions. Its prominence as a keyword also signals growing scholarly interest in the land-use dynamics, sustainability challenges, and governance mechanisms linked to oil palm expansion. In contrast, palm oil refers to the processed commodity derived from the crop, representing the economic and trade dimensions of the sector and drawing attention to research on global supply chains, market access, and sustainability certification. Together, these keywords delineate the interconnected production and environmental dimensions that shape the global discourse on oil palm plantations and deforestation.

The prominence of Indonesia (383 occurrences) and Malaysia (186) among the top keywords further underscores the geographical concentration of research in Southeast Asia, where oil palm expansion has been most pronounced. Similarly, keywords such as biodiversity (313), forest (190), agriculture (182), and tropical forest (154) indicate that the literature is heavily focused on ecological impacts, habitat change, and the spatial footprint of monoculture plantations.

Interestingly, new analytical and thematic directions have emerged in recent years, especially in 2024. Keywords such as spatial analysis and machine learning have appeared more frequently in temporal overlays, suggesting a growing integration of geospatial technologies and advanced computational methods into deforestation monitoring and prediction. The increased mention of India as a keyword also hints at a shift toward new regional case studies beyond the traditional Southeast Asian context. These findings reveal both the maturity and potential expansion of the field. Further examination of the literature's conceptual structure, a keyword co-occurrence, visualized in Figure 3, maps author keywords and Keywords Plus based on co-occurrence frequency, grouping them into thematic clusters through color-coded modularity analysis. The network reveals four dominant clusters, each representing a significant research focus. The red cluster, centrally anchored by keywords such as palm oil, deforestation, and land use change, represents the core environmental and land-use dynamics that define much of the field.

Table 1 Top 10 most relevant journals.

Source	Country	Year start	N of articl-es	N of citati-ons	Citation per article	H Index 2024 (SJR)	Journal Impact Factor 2024 (Clarivate)
Environmental Research Letters	United Kingdom	2009	54	2,378	44.0	201	5.6
Land Use Policy	United Kingdom	2011	46	1,916	41.7	171	5.9
PLoS One	United States	2011	42	2,505	59.6	467	2.6
Biological Conservation	Netherlands	2008	41	1,545	37.7	244	4.4
Conservation Letters	United States	2008	18	2,024	112.4	115	5.9
Forest Policy and Economics	Netherlands	2014	28	820	29.3	92	3.8
Journal of Cleaner Production	United Kingdom	2010	27	991	36.7	354	10
Proceedings of the National Academy of Sciences of the United States of America	United States	2009	19	4,523	238.1	896	9.1
Global Environmental Change: Human and Policy Dimensions	United Kingdom	2001	20	1,179	59.0	242	9.1
Global Change Biology	United Kingdom	2012	18	1,391	77.3	332	12

Table 2 Top 10 most frequently occurring keywords.

Keyword	Occurrences	Total link strength
Palm oil	1,056	13,981
Land use change	706	10,102
Deforestation	644	7,953
Oil palm plantation	447	7,242
Indonesia	383	5,330
Biodiversity	313	4,520
Forest	190	3,052
Malaysia	186	3,052
Agriculture	182	3,132
Tropical forest	154	2,346

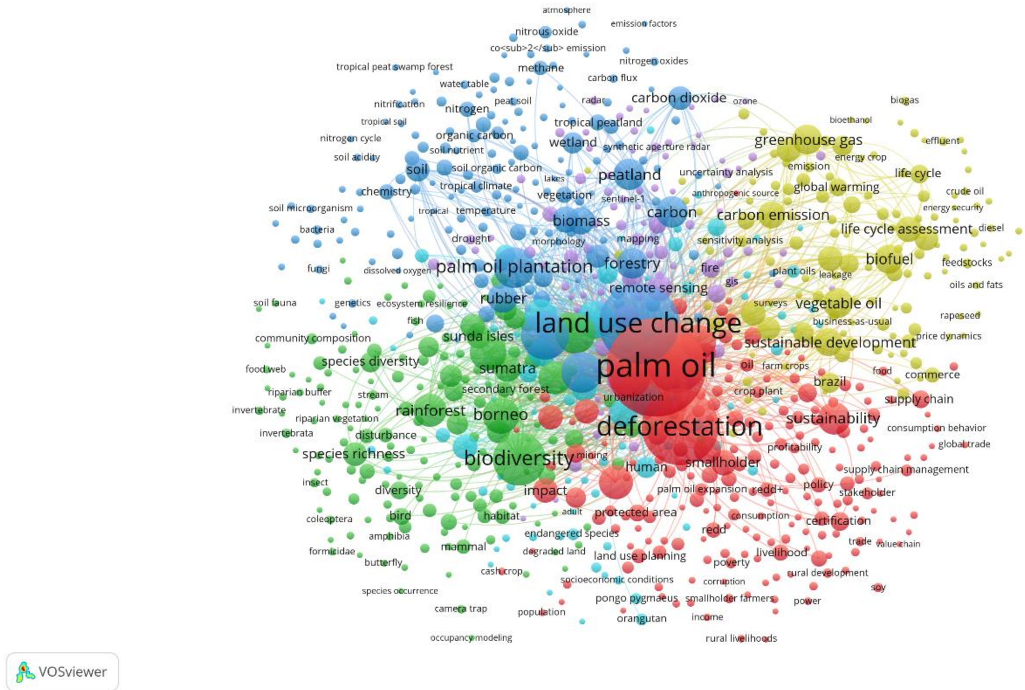

Figure 3 Keyword co-occurrence network

The green cluster focuses on biodiversity, species richness, and rainforest ecology, highlighting research on the ecological consequences of palm oil expansion. The blue cluster groups terms like peatland, carbon emissions, wetland, and biomass, corresponding to emissions accounting studies, peat degradation, and tropical carbon cycles. Meanwhile, the yellow cluster captures a more policy- and economy-oriented body of research, with keywords such as sustainability, life cycle assessment, supply chain, and biofuel, reflecting increasing attention to governance, global trade, and corporate responsibility.

The size of each node corresponds to the frequency of keyword usage, while the proximity and strength of links indicate co-occurrence intensity. As expected, palm oil, land use change, and deforestation form the densest and most central nodes, reinforcing their position as the conceptual anchors of the literature. Surrounding clusters show the thematic diversity that has developed over time, pointing to areas of convergence between ecological science, carbon accounting, and sustainability governance.

Collaboration Patterns and Influential Actors

Institutional analysis highlights the central role of a select group of universities and research organizations in shaping global research on palm oil and deforestation. As illustrated in Figure 4, the University of Göttingen in Germany is by far the most prolific institution, contributing 277 articles to the field. This reflects its sustained focus on land-use science, tropical ecology, sustainability governance, and long-standing collaborations with partners in Southeast Asia.

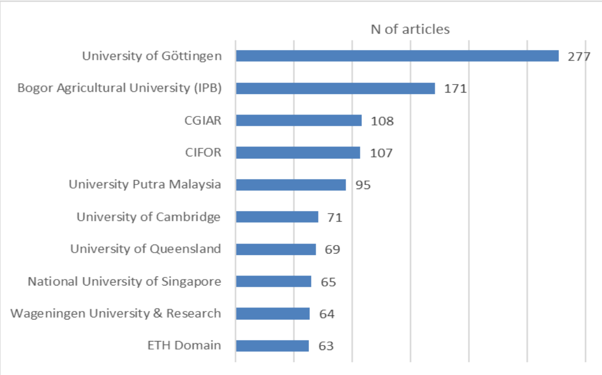

Figure 4 Top 10 most relevant affiliations, based on the number of articles.

Bogor Agricultural University (IPB University) in Indonesia follows as the second most productive affiliation, with 171 articles, underscoring Indonesia's increasing leadership in generating empirical and policy-relevant knowledge from one of the world's most affected regions. International research centers such as CGIAR (Consultative Group on International Agricultural Research) and CIFOR (Center for International Forestry Research) also rank highly, each contributing over 100 articles. These institutions are key in bridging scientific research and development practice across tropical forest landscapes.

Other notable contributors include Universiti Putra Malaysia, University of Cambridge, and University of Queensland, indicating strong engagement from producer and consumer country institutions. The presence of Wageningen University & Research, ETH Domain, and the National University of Singapore further reflects the international and interdisciplinary nature of the field, combining expertise in agronomy, policy, remote sensing, and environmental governance. The distribution of single-country and multiple-country publications offers important insight into the geopolitical structure of collaboration in palm oil and deforestation research. As illustrated in Figure 5, the United States leads overall international engagement, with 111 multiple-country publications and 88 single-country publications, making it the top country for corresponding authorship (199 articles total). This reflects the U.S.'s broad involvement in global environmental research and its frequent collaborations with both Global North and Southeast Asian partners.

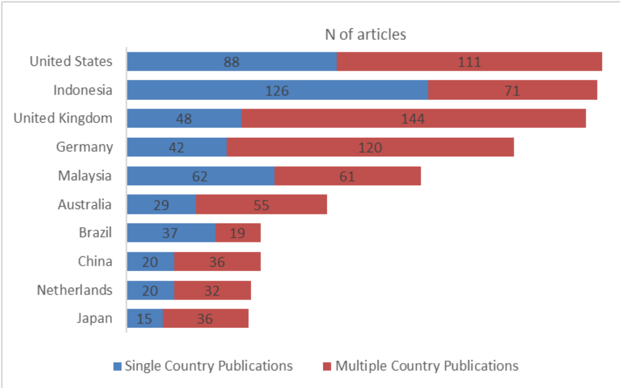

Figure 5 Distribution of single-country and multiple-country publications by author affiliation.

In contrast, Indonesia has the highest number of single-country publications (126), indicating a strong independent national research base. This is particularly notable given Indonesia's central role as the world's largest palm oil producer. The country's growing academic engagement is further underscored by its rising publication volume, which surpassed Malaysia in 2024, placing it second in overall annual output. However, Indonesia's relatively lower number of multiple-country papers (71) suggests room to expand its international collaboration footprint.

The United Kingdom dominates multiple-country publications, with 144 collaborative articles, reinforcing its status as a key node in global environmental science networks. Germany follows closely with 120 multi-country publications, reflecting its institutional investment in tropical land-use and forest governance research. Countries such as Malaysia, Australia, and Brazil also demonstrate balanced engagement across domestic and international publications, while China, Japan, and the Netherlands are more active through cross-border collaboration than domestic-only contributions.

The global collaboration map in Figure 6 illustrates the spatial distribution and intensity of co-authorship networks in palm oil and deforestation research. The map highlights strong transnational ties between institutions located in Europe (notably the United Kingdom and Germany), North America (particularly the United States), and Southeast Asia (especially Indonesia and Malaysia). These regions form the structural backbone of global scientific cooperation in this field. European institutions emerge as major hubs, with the United Kingdom acting as a central node that connects extensively with both Global South and Global North partners. Germany, too, demonstrates broad international collaboration, especially through land-use research and sustainability governance. The United States maintains dense linkages with both Asia and Europe, reflecting its position as a key contributor to cross-regional research projects and environmental science networks. On the producer side, Indonesia and Malaysia play vital roles within the collaboration landscape, engaging in both North–South and intra-Asian partnerships. While Indonesia leads in single-country publication volume, its collaborative reach is increasingly evident in partnerships with institutions in Europe and Australia. However, the map also reveals noticeably fewer connections among Global South countries themselves, suggesting that South–South collaboration remains under-developed.

The co-authorship network, visualized in Figure 7, provides insight into the collaborative structure of palm oil and deforestation research. Generated through VOSviewer, the map reveals several distinct author clusters, each representing closely linked research communities with frequent co-publications. At the center of the network is Erik Meijaard (purple cluster), who serves as a prominent bridge across multiple clusters, connecting authors focused on biodiversity, conservation science, and policy. His collaborations with researchers such as Ancrenaz M, Gaveau D, and Laurance W highlight a strong Southeast Asia-focused conservation community. Similarly, David Edwards and Lian Pin Koh anchor another influential group that connects tropical ecology with land use change, reflecting interdisciplinary research that links ecological modeling with remote sensing and policy applications.

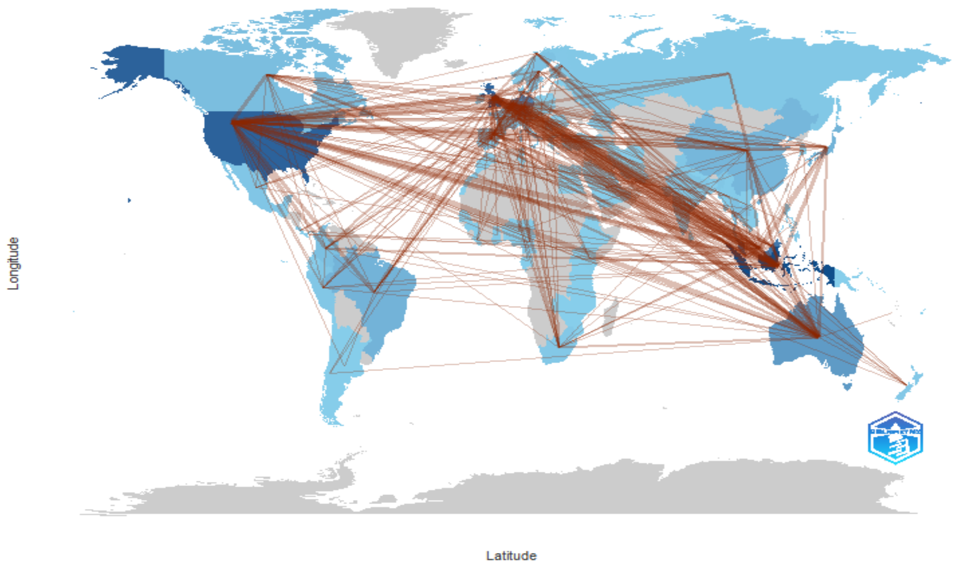

Figure 6 Collaboration world map

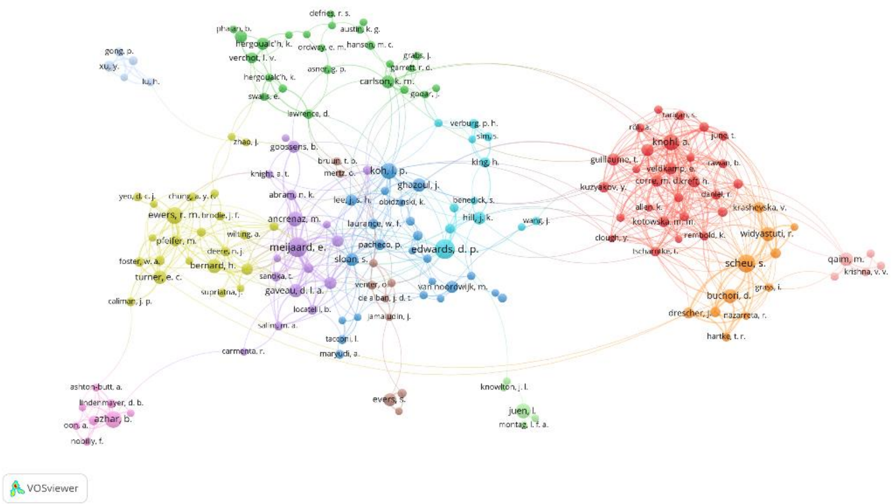

Figure 7 Co-authorship network

The red cluster, dominated by Knohl, A. and Scheu, S., represents a dense European collaboration network focused on carbon cycling, land use systems, and agroecological transitions. This group is notable for its internal connectivity and high publication volume, reflecting a cohesive research agenda rooted in landscape ecology and ecosystem processes. Another distinct cluster (purple) features Azhar, B., and collaborators, primarily focused on biodiversity outcomes in Malaysian plantation landscapes.

Several smaller but important clusters exist on the periphery, such as those involving Qaim, M., who integrates agricultural economics with deforestation and sustainability studies, and researchers like Turner, E., active in landscape ecology and species distribution modeling. The relatively limited number of South–South linkages in the network suggests that while international collaboration is robust, Global South institutions tend to collaborate more often with Global North partners than with each other.

Research Gaps, Shifts, and Emerging Narratives

The temporal distribution of keywords presented in Figure 8 provides valuable insight into the thematic evolution of palm oil and deforestation research over time. Early work (pre-2010) focused heavily on environmental and atmospheric science, with terms such as greenhouse gas, emission control, logging, and tropical deforestation dominating the landscape. These foundational topics reflect the initial focus on carbon emissions, climate impacts, and forest degradation associated with palm oil expansion.

From 2012 to 2018, the field began diversifying, as shown by the appearance and intensification of terms such as biodiversity, land use change, Southeast Asia, and deforestation. This period marks the emergence of ecological and geographic specificity, with Malaysia, Borneo, and peatlands becoming central case studies. The frequency and prominence of sustainable palm oil, expansion, and poverty around 2018–2020 point to a growing concern with socio-economic dimensions and sustainability governance.

More recently, trend topics have shifted toward technical innovation and methodological sophistication. From 2021 onward, keywords like spatial analysis, machine learning, land cover, smallholder, and passive acoustic monitoring have become increasingly prominent. These indicate a broader integration of remote sensing, AI tools, and participatory field methods into the analysis of deforestation dynamics. The emergence of India as a research hotspot also suggests a gradual geographical broadening of palm oil-related studies beyond traditional Southeast Asian contexts. To explore the temporal dynamics and emerging focus areas in the field, an overlay visualization of keyword co-occurrence was generated using VOSviewer. This map, shown in Figure 9, displays the average publication year of keywords, with colors ranging from dark blue (older topics) to yellow (newer topics), based on articles published between 2015 and 2020. As expected, the core thematic structure of the field continues to center around foundational keywords such as palm oil, land use change, and deforestation, which appear in green, indicating sustained relevance across multiple years. These terms form the backbone of the literature and are tightly linked to topics like biodiversity, rainforest, and Malaysia, reflecting early and ongoing ecological concerns related to tropical forest conversion.

Surrounding these central concepts, clusters of older research (dark blue nodes) emphasize carbon dynamics, including terms such as carbon dioxide, greenhouse gas, peatland, biomass, and carbon emission. These topics were heavily studied in earlier phases of the literature, particularly in the context of emissions accounting and land-based climate mitigation.

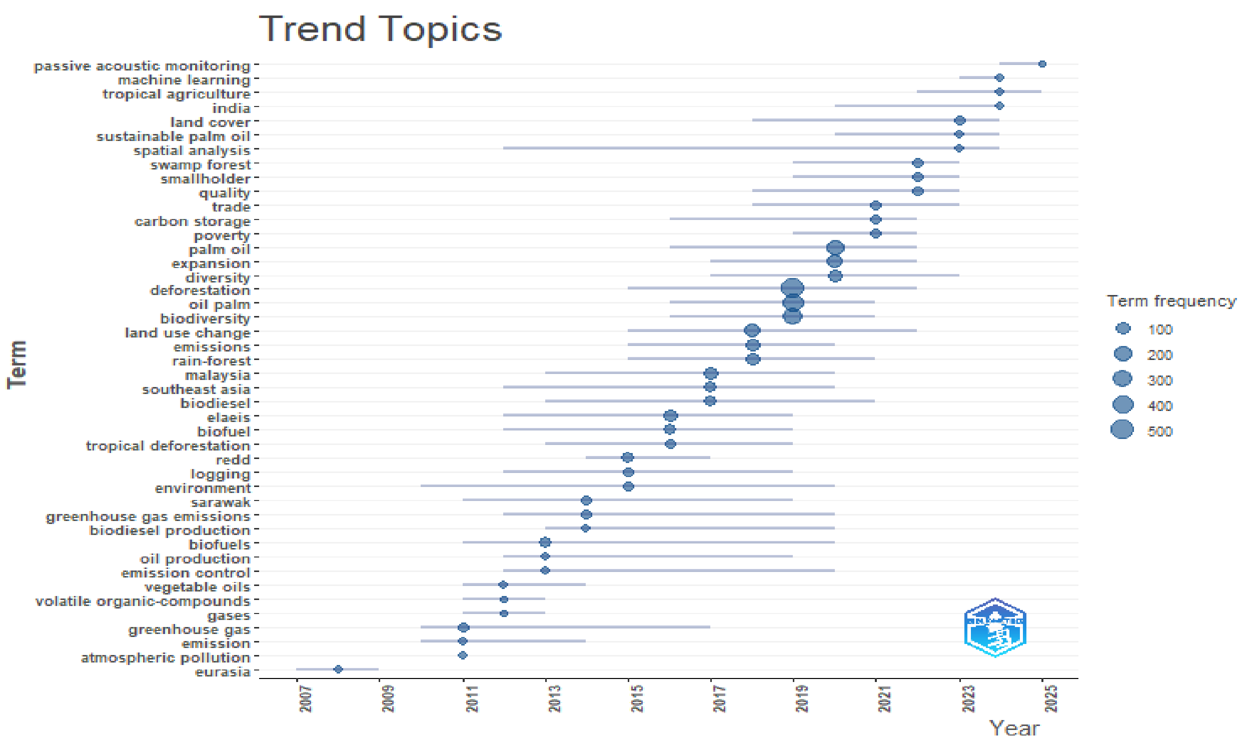

Figure 8 Overlay visualization of palm oil and deforestation research

In contrast, the yellow and light green nodes signal more recently emerging topics. These include sustainable development, life cycle assessment, certification, commerce, smallholder, and supply chain management, indicating a shift toward sustainability governance, socio-economic equity, and responsible sourcing frameworks. The growing visibility of keywords such as socio-economic conditions, human rights, and biofuel policies suggests broadening the research agenda to incorporate justice-oriented and policy-relevant themes. This visual and temporal evolution highlights the gradual diversification of the field moving from a strong ecological and carbon centric core toward more integrated approaches that include supply chain transparency, sustainability metrics, and socio-political dimensions, also suggests that palm oil research increasingly intersects with global governance and market-based interventions to mitigate tropical deforestation.

Future Research Agenda

There are several promising directions for research on palm oil and deforestation, especially if the goal is to build a more inclusive, interdisciplinary, and grounded body of knowledge.

To begin with, it is hard to ignore how much the current literature leans toward ecological and technical framings. That's not bad, after all, biodiversity loss and land use change are at the heart of this issue, but there's still a noticeable absence of work that foregrounds justice, local experiences, or power dynamics. Terms like land rights, customary tenure, or indigenous knowledge barely appear in the keyword networks. Future studies would engage more with political ecology, critical agrarian studies, and decolonial perspectives to ask what is happening on the ground, but for whom, by whom, and with what consequences.

Another important agenda item is changing who gets to do the research or who leads it. While it is encouraging to see Indonesia's productivity rise and overtake Malaysia in 2024, most influential papers still come from institutions in Europe and North America. Strengthening South-South collaborations and supporting Southern-led initiatives is crucial, not just for equity, but for producing context-sensitive, locally-informed insights that might otherwise be missed.

On the methods side, there's a clear shift happening. Topics like spatial analysis, machine learning, and even India are emerging strongly in recent years. This approach suggests the field is branching out, technologically and geographically. Integrating remote sensing, AI, and big data can deepen our understanding of where and how forest conversion occurs, but it also raises questions about access to data, digital capacity, and interpretive authority. Pairing high-tech tools with grounded fieldwork and participatory approaches could help bridge this gap.

The global policy landscape is also shifting, with instruments like the implementation of EUDR, there's a lot to unpack: How are producing countries responding? What does compliance look like on the ground? Are smallholders being heard, or sidelined? We need more research that not only evaluates policy effectiveness, but also looks at questions of legitimacy, ownership, and procedural fairness, especially from the perspective of those most directly affected.

And finally, there's a more philosophical, but no less urgent, question to consider: whose knowledge counts in this debate? Much of the literature still reflects a top-down, global framing of deforestation, while local voices and alternative worldviews remain under-represented. Future work should make space for different ways of knowing, whether through oral histories, community mapping, or collaborative ethnography.

In short, the next generation of palm oil and deforestation research should aim to be broader, faster, and more equitable, reflexive, and responsive to context. It requires methodological diversity, ethical awareness, and critical engagement with scientific and political dimensions of land use change.

Finally, this bibliometric analysis, while global in scope, also reinforces the strategic importance of Indonesia. As a research hub and a policy battleground, Indonesia is uniquely positioned to lead future work integrating scientific evidence, grassroots insights, and governance innovation. Supporting Indonesia's role in shaping the global research agenda will be crucial for advancing knowledge and action in the palm oil-deforestation nexus.

CONCLUSION

This study provides the first comprehensive bibliometric and science mapping analysis of global palm oil and deforestation research. Drawing from 1,622 peer-reviewed journal articles indexed in Scopus and Web of Science, and using Bibliometrix and VOSviewer for analytical tools, the study maps the structure, evolution, and collaborative patterns that define the knowledge landscapes of this increasingly critical field.

The results show a significant and sustained growth in research output over the past two decades, with a peak in 2019. Most of this literature is published in high-impact, interdisciplinary journals and led by scholars and institutions based in Europe, North America, and Southeast Asia. As a research subject and publishing actor, Indonesia has risen in visibility, recently surpassing Malaysia in annual output. However, Global North institutions continue to dominate in terms of co-authorship networks and citation impact.

Thematically, the literature has been primarily framed through ecological and technical lenses, strongly focusing on biodiversity loss, land use change, emissions, and sustainable certification. Keyword and co-citation analyses reveal a mature core around land systems and conservation, but also point to a growing body of work on machine learning, spatial analysis, and new regional contexts like India. However, justice-oriented topics, such as land rights, indigenous knowledge, and community governance, remain underrepresented, signaling a persistent gap in the field.

Looking forward, the study highlights the need for a more inclusive and reflexive research agenda that strengthens Southern-led scholarship, encourages South–South collaborations, and incorporates methodological pluralism, including qualitative and participatory approaches. As policies like the EUDR reshape governance landscapes, research must also grapple with equity, legitimacy, and local agency questions.

The study advances bibliometric scholarship by identifying the key contributors, thematic trajectories, and collaboration structures within this literature. It offers a strategic foundation for researchers, policymakers, and funders seeking to build more just and sustainable pathways in the palm oil-deforestation nexus.

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Automatic Water Flow-Based Soil Moisture Monitoring System Oil Palm Nurseries

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ABSTRACT

There are many challenges and obstacles that often arise when caring for agricultural crops until harvest time arrives. One of the challenges in caring for oil palm seedlings is controlling soil moisture and maintaining the right water content for the seedlings. Many seedlings die because they do not get enough water, and sometimes extreme weather conditions make it impossible to water the plants. Farmers typically do not have the time to regularly monitor soil moisture and irrigation, especially for large areas. Based on this issue, there is a solution in the form of a soil moisture monitoring system with automatic irrigation based on the Internet of Things (IoT) to assist and simplify the management of these challenges. This study aims to design a soil moisture monitoring system with automatic irrigation to help farmers maintain soil moisture in seedbeds. This study uses the Research and Development (R&D) method to develop the previous system as a solution to the problem and improve the previous device. The result of this study is a prototype of an automatic irrigation-based soil moisture monitoring system with a DHT11 sensor and a soil moisture sensor. This system was tested based on calibration results showing that the sensor works with a regression equation. The coefficient of determination obtained for the DHT11 sensor was 0.95 and 0.89, for the soil moisture sensor was 0.91, and for the ultrasonic sensor was 1.0. Based on the regression equation obtained, the system can respond well to changes in temperature, humidity, and water levels to monitor soil moisture in seedbeds.

Keywords: Automatic Irrigation, internet of things, nursery, regression coefficient, soil monitoring system

INTRODUCTION

Indonesia is one of the largest producers of palm oil among countries in the world. (Nugroho *et al.* 2021). Palm oil as the primary raw material in the production of cooking oil, which is an essential commodity in daily life. According to a report from the Central Statistics Agency (BPS) in 2023, based on the area of land used, the total area is Oil palm plantations continued to increase from 2019 to 2023, but growth has nearly stagnated. By 2023, the total area of oil palm plantations is projected to reach 15.93 million hectares.

In order to obtain high-quality palm oil, palm trees are cared for from the moment they are planted. (Putro and Rasyid 2024). The palm oil seedling cultivation process requires monitoring of the condition of the seedlings, soil, and water content. Currently, there are many challenges and obstacles that hinder the cultivation process until the planting stage. (Saputra *et al.* 2023). One of the challenges faced is soil moisture composition and water irrigation. Data from the

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central statistics agency (BPS) shows that more than 55% of farmers in Indonesia still rely on unmeasured manual irrigation systems, which often results in water wastage and uneven irrigation. Controlling soil moisture levels and proper irrigation systems It is essential to maintain the seedlings until the planting season (Ningsih *et al.* 2021). Dependence on traditional irrigation methods is one of the obstacles to maximizing optimal palm oil seedlings (Effendi *et al.* 2024). Manual irrigation systems that are not adapted to environmental conditions often result in a mismatch between plant water requirements and the amount of water supplied. This problem is exacerbated by climate change, which causes unpredictable rainfall patterns (Utomo *et al.* 2021).

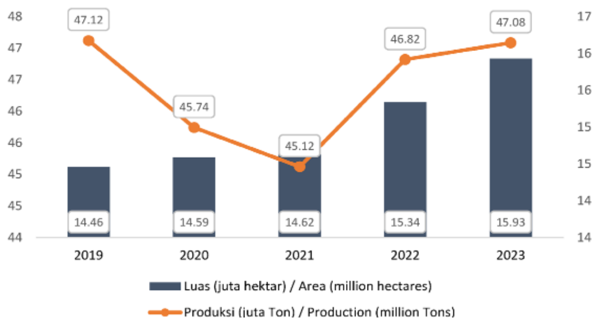

Figure 1 Area and Production of Indonesian Palm Oil, 2019–2023

The lack of an adequate system to monitor soil moisture and water availability makes it difficult for farmers to adjust the needs of oil palm seedlings to environmental conditions (Mahdi and Kasoni 2019). Palm oil farmers also do not have enough time and resources to monitor the condition of the seedlings. By utilizing current technological development solutions can be found to overcome these problems. Technological developments in the field of electronics can be utilized to overcome problems related to soil moisture monitoring and irrigation. Sensor technology can be used to monitor environmental conditions for consideration in irrigating seedling nurseries (Suprasetyo *et al.* 2023). When environmental conditions and soil moisture levels allow for irrigation, then he automatic irrigation system will turn on irrigation gate (Novrizal 2019). This tool is equipped with IoT technology that can be monitored remotely via a smartphone. It is hoped that the use of this technology can help increase agricultural production, improve community welfare, and protect the environment.

MATERIALS AND METHODS

His study uses the Research and Development (R&D) method in assessing and designing research products. The tools produced are developments from previous studies, as well as experimental models to test the effectiveness of the tools when implemented (Sihombing *et al.* 2022). This activity will be carried out over a period of two months. The design of the tools and systems will be conducted offline at the Physics Laboratory, Padang State University, Jalan Prof. Dr. Hamka, Air Tawar Padang, West Sumatra. The electronic components that make up the soil moisture and automatic irrigation monitoring system are ESP32 as a microcontroller, DHT11 sensor, Soil Moisture sensor, Ultrasonic sensor, servo motor, water pump, relay module, jumper cable, and USB cable. Data collection techniques were carried out through observation and testing of the sensors and the system as a whole.

Data analysis was performed by conducting verification tests, meaning that after the optimal design was determined, the predicted response of the optimal design was also known. Then, verification experiments were conducted to compare the results with the predicted response. If the predicted response and the verification experiments were close to each other, it could be concluded that the design was adequate (Darusman and Sulaiman 2023). Conversely, if the verification experiment results are far from the predicted results, then the design is said to be inadequate. This device was designed as a prototype that illustrates the physical form of the system. Ultrasonic sensors are positioned at the top of the irrigation system, then the design is said to be inadequate. This device was designed as a prototype that illustrates the physical form of the system. Ultrasonic sensors are positioned at the top of the irrigation system, DHT11 sensors are installed around the field area, and Soil Moisture sensors are inserted into the soil.

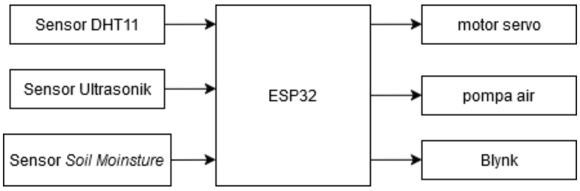

Figure 2 Working principle of tool components

Figure 3 is a mechanical design prototype of a soil moisture monitoring and control system for agricultural land. The tool works based on the soil moisture content in the targeted area. Soil moisture content is measured using the FC-28 Soil Moisture Sensor (Putra *et al.* 2024). All measured data will be sent to the ESP32. If the soil moisture is within a certain limit (moisture < 50%), the irrigation gate will open. When it reaches or exceeds a certain limit, the irrigation gate will close automatically. When the irrigation gate is open, the water in the irrigation system will automatically decrease and the water level will also decrease. An ultrasonic sensor will be used to measure the water level in the irrigation system. The ultrasonic sensor is placed 5 cm above the water surface. As the water level decreases, the distance between the sensor and the water surface automatically increases. If the distance between the ultrasonic sensor and the water surface exceeds 5 cm, the water pump will automatically turn on to refill the irrigation system.

The irrigation gate is operated using a servo motor as an actuator. When soil moisture is insufficient, the ESP32 will send a signal to the servo motor to open the irrigation gate. When moisture levels are adequate, the ESP32 will send a signal to the servo motor to close the irrigation gate again. Data from the ESP32 will be transmitted to the Blynk application.

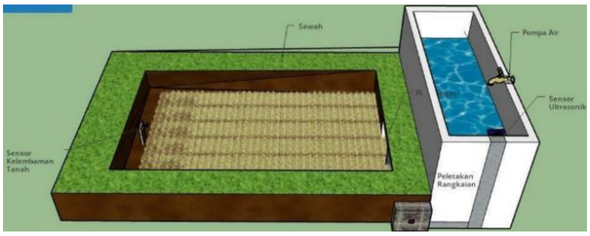

Figure 3 Design prototype system design

RESULTS AND DISCUSSION

The result of designing a prototype system for monitoring and controlling soil moisture and automatic irrigation based on IoT connected to the Blynk application. The size of the prototype system illustrates the design of the system on actual land. The hardware is designed with acrylic on irrigation, equipped with ultrasonic sensors and DHT11, while the Soil Moisture sensor is inserted into the soil.

Figure 4 Testing of equipment

System Software

The system software describes the mechanism for sending data from the ESP32 processing results to a cloud platform or server via a Wi-Fi network connected to the internet using the Wi-Fi module integrated into the ESP32. The data sent to the cloud is then stored and can be accessed by users through an interface via the Blynk application. In the Blynk application, the system measurement results can be displayed on a smartphone or computer screen to view the output from the device. The functionality of the DHT11 sensor in measuring temperature index in Figure 5 was tested under several conditions, namely placing the sensor at room temperature and placing the sensor outdoors. The sensor was also calibrated by comparing the measurement results with a standard device, namely a digital anemometer. The results obtained were then plotted in the following graph to find the sensor calibration equation. The Figure 6 shows a comparison of air temperature measurements with various treatments between the sensor and standard tools. The graph shows a linear regression relationship for both the sensor and standard tool measurements. The coefficient obtained for the DHT11 sensor is 0.97 with a calibration equation of $y = 0.035x + 25.85$ and a standard tool coefficient of 0.90. Based on testing, the calibration results are close to a coefficient of 1, meaning the sensor can detect environmental temperature precisely and accurately.

The Figure 6 shows a comparison of air humidity measurements with various treatments between the sensor and the standard device. The graph shows a second-order polynomial regression relationship for both sensor and standard device measurements. The coefficient obtained for the DHT11 sensor is 0.96 with the calibration equation $y = 0.0009x^2 - 0.0101x + 65.054$, and the coefficient for the standard instrument is 0.95. Based on the calibration test results, the coefficients are close to 1, indicating that the sensor can detect environmental temperature accurately and precisely.

Table 1 Test data for the DHT11 sensor in measuring temperature

No	Time (s)	Device Temperature (C)	Temperature on the standard device (c)	Percentage error (%)
1	10	26,3	26,6	1,12
2	20	26,4	26,4	0
3	30	26,8	26,6	0,75
4	40	27,2	26,9	1,11
5	50	27,8	27,5	1,09
6	60	28,1	28,01	0,32
7	70	28,3	28,1	0,71
8	80	28,5	28,2	1,06

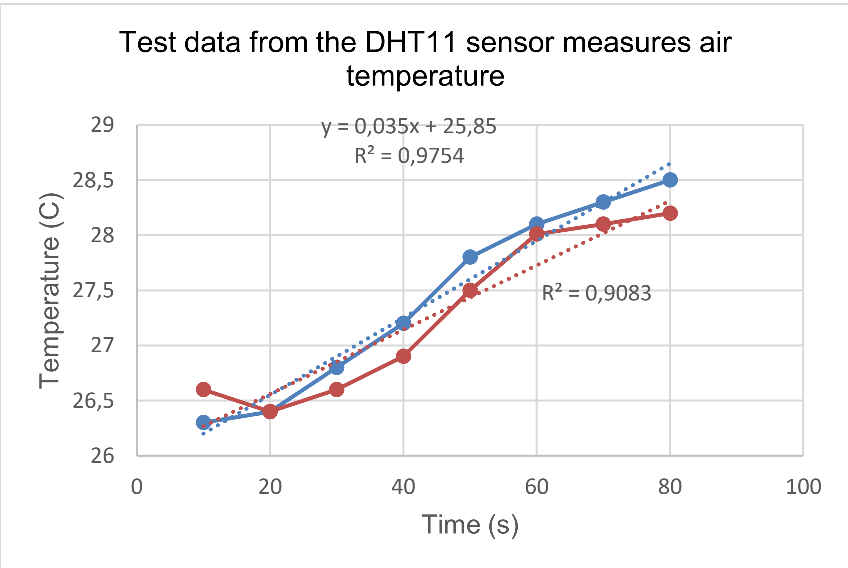

Figure 5 Testing graph of the DHT11 sensor in measuring temperature

Table 2 Testing the DHT11 sensor in measuring environmental humidity

No	Time (s)	Humadity of Device (%)	Standard instrument humidity (%)	Percentage error (%)
1	10	65	63,3	2,68
2	20	65	63,5	2,36
3	30	66	63,5	3,93
4	40	66	64	3,12
5	50	67	64,1	4,52
6	60	67	65	3,07
7	70	69	68	1,47
8	80	70	69	1,44

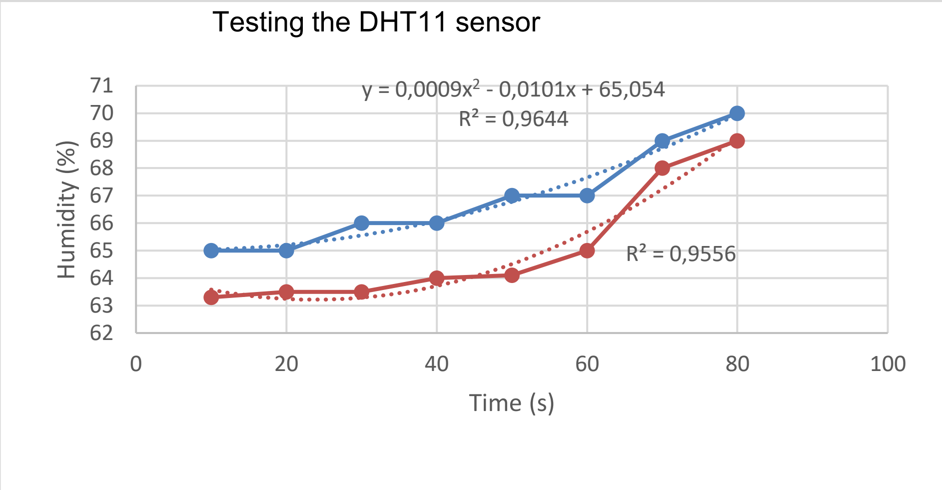

Figure 6 Graph of DHT11 sensor testing in measuring humidity

Soil Moisture Sensor Testing

Based on the calibration results of the Soil Moisture sensor with analog values in table 3, the uncertainty value is very small (in the range of 0.1–1.3%), indicating good accuracy of the sensor. The influence of soil conditions (moist, room temperature, or dry) does not seem to have a significant impact on the relationship between analog values and moisture in the given data. The relationship between analog values and soil moisture percentage is linearly decreasing, meaning that as soil moisture increases, the analog values of the sensor decrease.

Ultrasonic Sensor Testing

Based on the data in table 4, the ultrasonic sensor measurement values range from 2.2 cm to 12.91 cm. This data reflects the distance measured by the sensor. The ruler values show the actual distance reference values ranging from 2 cm to 12 cm. The calibration values are slightly different from the original sensor results, reflecting the sensor accuracy improvement process. The uncertainty indicates the error level of the sensor measurements compared to the actual values. The uncertainty values vary between 3.1% and 9.1%, with the average tending to be smaller at greater distances. The ultrasonic sensor has a fairly good level of accuracy.

The graph in Figure 7 shows the linear regression relationship of the sensor measurements. The coefficient obtained for the sensor is 1 with a calibration equation of $y = 0.9247x + 0.3397$. Based on the test results, the calibration coefficient is close to 1, meaning that the sensor can detect the ambient temperature precisely and accurately. The results of the system performance test measurements in table 4 showed temperature values ranging from 26.2°C to 33.2°C. The temperature tended to increase as the data changed. The humidity values ranged from 0.1 to 58%. Humidity tends to increase with higher temperatures. From the measurements, it was found that if humidity is below 40% and temperature is above 27°C, the servo motor will activate, and when humidity exceeds 40%, the servo motor will deactivate. If humidity exceeds 40%, the pump will shut off.

Table 3 Soil moisture sensor testing data

No	Sensor measurement	Calibration	Uncertainty (%)	Soil conditions
1	0	4089,1	0,1	Very humid
2	9	3716,9	0,1	Moist
3	17	3386,1	0,2	Moist
4	23	3138,0	0,1	Room Temperature
5	32	2765,8	0,2	Room Temperature
6	44	2269,5	1,3	Room Temperature
7	53	1897,3	0,5	Dry
8	64	1442,4	1,7	Dry

Table 4 Ultrasonic sensor measurement data

No	Sensor (cm)	Ruler (cm)	Calibration	Uncertainty
1	2,2	2	2,374	9,1
2	2,85	3	2,975	5,3
3	4,13	4	4,159	3,1
4	5,76	6	5,666	4,2
5	7,37	7	7,155	5,0
6	8,03	8	7,765	0,4
7	8,66	9	8,348	3,9
8	11,83	11	11,279	7,0

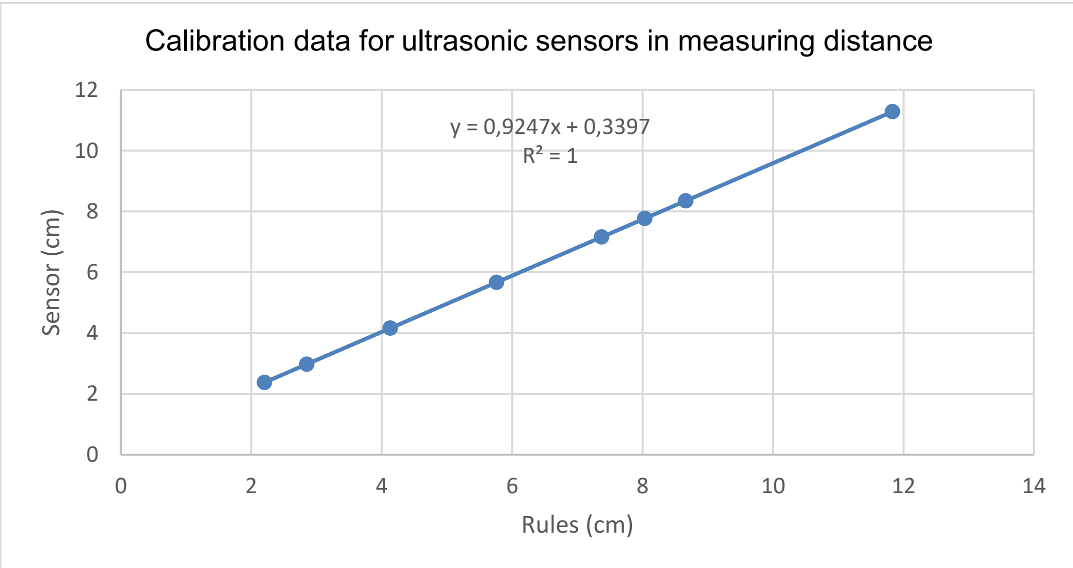

Figure 7 Graph of ultrasonic sensor testing in measuring distance

Table 5 Testing of the device system

No	Temperature (°C)	Humidity	Water distance	Servoak Motor Status	Pump Status
1	26.20	0.1%	5 cm	off	pump off
2	30	35 %	8 cm	on	pump on
3	31	43%	7 cm	off	pump off
4	31	45%	7 cm	off	Pump off
5	29.2	20%	8 cm	on	pump on
6	30.7	52%	4 cm	off	pump off
7	33	36%	5 cm	on	pump on
8	33.1	56%	6 cm	off	Pumpoff

CONCLUSION

This IoT-based automatic irrigation system measures soil humidity periodically and automatically regulates water flow, improving efficiency compared to conventional methods. The system was tested based on the calibration coefficients of each sensor: DHT11 for temperature and humidity at 0.97 and 0.96, Soil Moisture for soil moisture at 0.91, and Ultrasonic for water level at 1.0 and 0.96.

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Design and Feasibility Analysis of an integrated Zero-Waste Palm Oil biorefinery for Sustainable Aviation Fuel Production and Greenhouse Gas Mitigation

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ABSTRACT

This study aims to design and assess the technical, environmental, and economic feasibility of an integrated Zero-Waste Palm Oil biorefinery for the production of Sustainable Aviation Fuel (SAF) and other value-added co-products. A quantitative-descriptive approach was employed, integrating process simulation using Aspen Plus V14, Life Cycle Assessment (LCA), and financial modeling to evaluate the system's performance and sustainability. Primary data were obtained from operational palm oil mills. In contrast, secondary data were sourced from the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), Statistics Indonesia (BPS), and the Ministry of Energy and Mineral Resources (ESDM) during 2023–2024. The results demonstrate that the integrated biorefinery configuration, which combines thermochemical conversion pathways (pyrolysis, gasification, and Fischer–Tropsch synthesis) with biochemical processes (anaerobic digestion), achieves a mass conversion efficiency of 58.4 percent, net energy efficiency of 72 percent, and an Energy Return on Investment (EROI) of 4.97, exceeding the global bioenergy feasibility threshold of three. The LCA results indicate total Life-cycle emissions of 17.3 g CO_2-eq per MJ, representing an 80.6 percent reduction relative to fossil-based Jet A-1 fuel, thereby meeting both CORSIA and RED II sustainability standards. The system also achieves a 95 percent reduction in solid residues, effectively realizing a near-zero-waste operation. Financial modeling reveals a net present value (NPV) of USD 68.2 million, an internal rate of return (IRR) of 17.6 percent, and a payback period of 6.2 years, confirming the project's economic viability. Overall, this model establishes a scalable pathway for decarbonizing the palm oil industry through circular bioeconomy principles and positions Indonesia as a potential global hub for SAF production aligned with international carbon reduction targets.

Keywords: Palm Oil WasteCircular Bioeconomy, Life Cycle Assessment (LCA), Sustainable Aviation Fuel (SAF), Zero-Waste biorefinery

INTRODUCTION

The palm oil industry is a fundamental pillar of the Indonesian economy, serving as a major contributor to the country's foreign exchange and providing extensive employment (BPS & Kementan 2023). This sector's significant contribution to Gross Domestic Product (GDP) aligns with national efforts to achieve the Sustainable Development Goals (SDGs), particularly SDGs 8 and 9. This strategic position positions the palm oil industry not only as a national economic engine but also as a key actor in the transition to a global green economy.

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However, this central role carries consequences in the form of global demands to balance social, economic, and environmental aspects throughout the production chain (BPS & Kementan 2023).

The main challenge facing the palm oil industry today lies in its legitimacy regarding sustainability. To remain competitive in international markets and uphold its global reputation, the sector must proactively address its environmental impacts through the implementation of sustainable production practices. Compliance with certification schemes such as the Roundtable on Sustainable Palm Oil (RSPO) and the adoption of environmentally friendly production models are prerequisites for maintaining market access and attracting green investment (Judijanto 2025). In this context, the innovations developed must be able to generate measurable increases in economic output while providing significant ecological benefits, in line with SDGs 13 and 15.

Environmental issues facing the palm oil sector, such as deforestation, land degradation, and biodiversity loss, further reinforce the urgency of adopting a more comprehensive sustainability strategy (Judijanto 2025). One promising approach is applying the concept of circular bioeconomy. This closed-loop production system maximizes the utilization of all biomass fractions and converts waste into value-added resources (Cheah *et al.* 2023). In this paradigm, waste is no longer viewed as a residue to be discarded, but rather as a potential raw material for bioenergy and bioproduct innovation.

The logical evolution of the circular bioeconomy concept in the palm oil industry is a transition towards a sustainable, zero-waste palm oil mill model. Failure to manage waste, especially liquid waste that has the potential to produce large amounts of greenhouse gas emissions, can negate the industry's positive claims about achieving the SDGs. Therefore, the transformation to a palm oil mill with a zero-waste concept is essential. Zero-waste is not just a strategic choice, but an urgent environmental mandate to ensure a long-term contribution to global decarbonization.

In parallel, global demands for carbon footprint reduction have opened up massive new markets for sustainable fuels, especially Sustainable Aviation Fuel (SAF). The international civil aviation sector is targeting net-zero carbon emissions by 2050, as set out by the International Civil Aviation Organization (ICAO 2021). The implementation of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) strengthens this mandate by providing a globally binding regulatory framework (ICAO 2020). In this context, SAF is recognized as the most effective technology to support decarbonization, with an estimated contribution of 65% to the total emission reductions required by 2050 (IEA 2022; IATA 2024).

However, there is a significant supply gap between global SAF demand and production capacity. SAF production in 2025 is estimated to reach only 2 million tons, far below the demand of approximately 500 million tons by 2050 (IRENA 2023). This gap of 498 million tons opens up a strategic opportunity for countries with high biomass potential, such as Indonesia to become major suppliers of SAF. However, successful entry into this market is primarily determined by the availability of advanced feedstock that meet international sustainability criteria (IEA 2022; IATA 2024).

In the context of palm oil, the use of crude palm oil (CPO) as a raw material for biofuel faces criticism over the “food versus fuel" debate. To avoid this conflict, the direction of policy and research must shift to using palm oil residue or waste as an advanced feedstock that does not compete with food production. This approach transforms waste from an environmental liability into a high-value strategic asset that meets global sustainability standards (Handoko & Lim 2022; IEA 2022).

Indonesia has an enormous supply of palm oil waste, including lignocellulosic fractions such as empty bunches, fiber, shells, and liquid waste. Palm Oil Mill Effluent (POME). However, the energy and biochemical potential of this resource have not been optimally utilized, with most of the waste still used for low-value applications such as fertilizer or fuel co-firing (Cheah *et al.* 2023; Jafri *et al.* 2021). For this reason, integrating a biorefinery is recommended as a strategy to convert the entire waste fraction into a portfolio of value-added products, including SAF.

One of the main focuses in design biorefinery as an integrated approach is mitigating methane (CH_4) emissions from POME. If left untreated, POME becomes a major source of GHG emissions in the palm oil supply chain due to its much higher global warming potential than CO_2 (Anwar *et al.* 2024). POME processing through technology anaerobic digestion allows for methane capture for renewable energy use, while simultaneously reducing the carbon intensity of the final product. Studies show that implementing this system can reduce emissions by up to 65,529 tons of CO_2 equivalent per year (Anwar *et al.* 2024). Therefore, the integration of POME treatment is key to legitimizing the waste-based SAF market under CORSIA standards and the Renewable Energy Directive II (REDII) of the European Union.

Although the literature has highlighted the potential of biorefinery Palm oil and its waste utilization (Cheah *et al.* 2023; Jafri *et al.* 2021), there is a research gap in comprehensive technical modeling and sustainability validation. Previous research has not integrated all waste fractions into a single system design optimized for SAF production, adhering to the principles of sustainability. Zero-waste. Therefore, the scientific novelty of this study lies in the proposed design. An integrated zero-waste biorefinery that processes 100% of PKS waste, with an orientation on three main pillars: technical optimization, sustainable financial feasibility, and verified total GHG emission mitigation through Life Cycle Assessment (LCA).

This research specifically seeks to answer three main questions: (1) how to design and configure integrated bio-refinery technically optimal and financially sustainable to convert the entire palm oil waste fraction into SAF and value-added by-products; (2) to what extent the total GHG emission mitigation level that the model can achieve zero-waste and how LCA verifies CH_4 emission reductions from POME; and (3) what implementation strategies and policy frameworks are most effective in accelerating the adoption of this technology in the national palm oil industry.

The primary objective of this research is to design and evaluate an Integrated Zero-Waste Palm Oil biorefinery that is both technically optimized and financially sustainable for converting all fractions of palm oil waste into Sustainable Aviation Fuel (SAF) and other value-added co-products. Specifically, this study seeks to address three fundamental research questions: first, how to develop a biorefinery configuration that maximizes energy recovery and conversion efficiency while maintaining long-term economic feasibility; second, to what extent the proposed system can mitigate total greenhouse gas (GHG) emissions through Life Cycle Assessment (LCA) verification, particularly focusing on methane (CH_4) emission reductions from Palm Oil Mill Effluent (POME); and third, what strategic policy and institutional frameworks are required to accelerate the adoption of zero-waste biorefinery technologies within the Indonesian palm oil industry.

The novelty of this research lies in its integrated approach, which combines thermochemical and biochemical conversion pathways within a single biorefinery system, supported by empirical LCA modeling tailored to Indonesia's tropical context. Unlike previous studies that examine palm oil waste valorization in isolation, this study provides a holistic systems model that quantifies both environmental performance and financial viability through cross-validation between process simulation and sustainability indicators.

The significance of this research extends beyond academic contribution. It provides a scalable blueprint for implementing industrial decarbonization and a circular bioeconomy in the palm oil sector, demonstrating how waste-to-fuel conversion can serve as a strategic pillar of Indonesia's energy transition and global carbon neutrality commitments under the Paris Agreement and CORSIA frame-works.

MATERIALS AND METHODS

This study uses a quantitative-descriptive approach integrating process engineering, energy, and economic analyses to assess the technical feasibility and sustainability of an integrated Zero-Waste Palm Oil biorefinery model. This approach aims to produce a system design that is thermodynamically efficient, economically viable, and compliant with the circular economy principles of the palm oil industry.

This research utilizes two types of data: primary and secondary. Primary data were obtained through technical observations at palm oil mills (PKS) and semi-structured interviews with industry operators regarding waste management and process energy consumption. Secondary data are sourced from official publications and previous studies, including the Ministry of Agriculture (2024), IEA Bioenergy (2023), World Bank Commodity Outlook (2024), IRENA (2022), OECD Bioeconomy Report (2024), and scientific articles. Secondary data are used as parameters for process simulation with Aspen Plus V14 software, incorporating biomass characteristics, calorific value, and reaction parameters for pyrolysis, gasification, Fischer–Tropsch Synthesis (FTS), and anaerobic digestion (AD) units.

The analysis was carried out in three stages, namely:

1. Technical and Energy Analysis is carried out by compiling mass and energy balances for all waste fractions (EFB, PKS, POME) and calculating conversion efficiency using process simulation.
2. Environmental Analysis conducted through a cradle-to-gate Life Cycle Assessment (LCA) approach, referring to the ISO 14040/44 standard to assess the potential for carbon emission reduction and resource efficiency.
3. Financial analysis using a discounted cash flow model with Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PP) indicators to determine the economic feasibility of a biorefinery system.

Data validity was ensured through source triangulation, which involved comparing simulation results with empirical data from industry and international technical literature. Reliability was tested through sensitivity analysis of key variables such as SAF prices, raw material costs, and energy efficiency, to assess the stability of model results against market fluctuations and operational conditions. Furthermore, the research results were validated through cross-country comparisons with similar studies in Malaysia and Thailand. These comparisons demonstrated the congruence between energy efficiency and financial performance, thus ensuring the robustness of the simulation results. For further understanding, the methodology framework has represented in the figure 1.

RESULTS AND DISCUSSIONS

Biorefinery Design and Mass Balance for PKS Waste Conversion

The diagram in figure 2 illustrates an integrated palm oil biorefinery scheme designed to convert all palm oil mill waste fractions into high-value products, with maximum technical efficiency and without

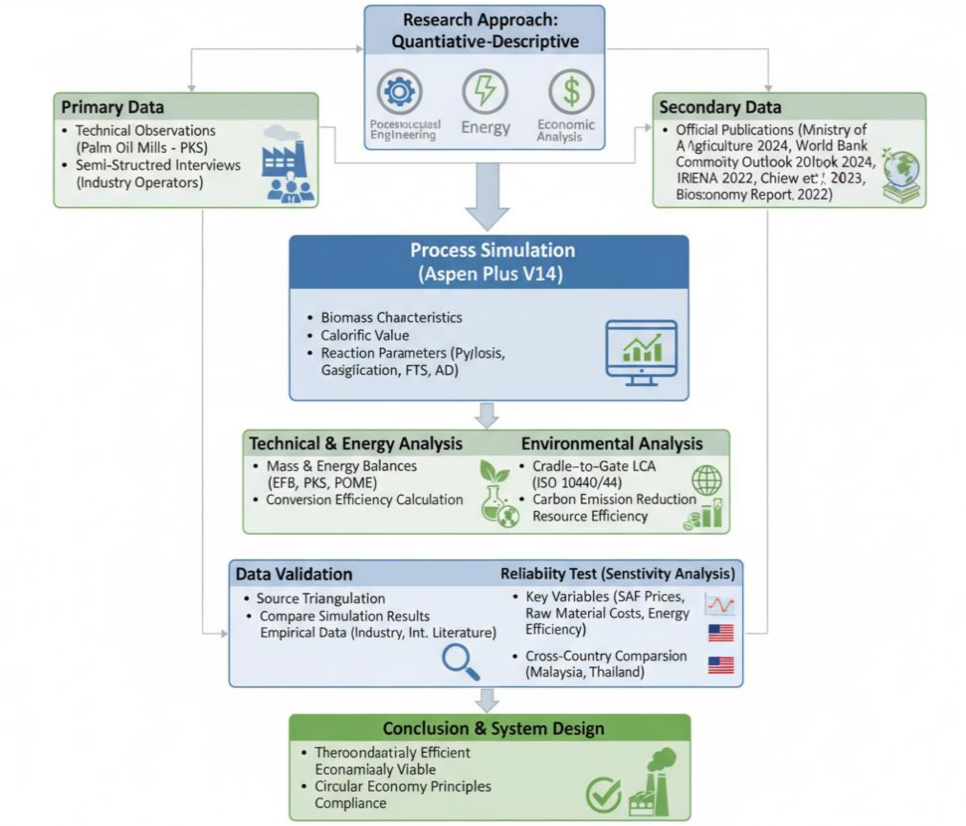

Figure 1 Methodology framework

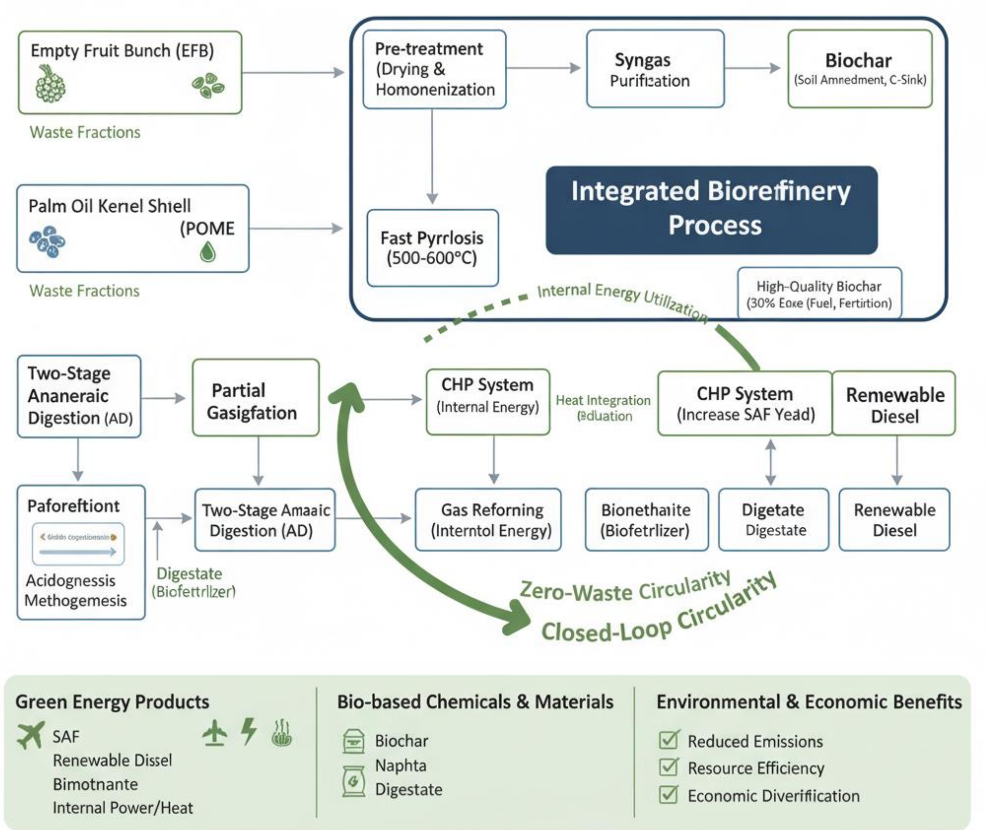

Figure 2 Schematic design of an integrated biorefinery palm oil mill waste

generating significant residues. This design places the integrated biorefinery process at the center, receiving three main types of waste: Empty Fruit Bunch (EFB), Palm Kernel Shell (PKS), and Palm Oil Mill Effluent (POME).

This integrated biorefinery configuration is designed to maximize the utilization of all palm oil mill waste fractions by integrating thermochemical, biochemical, and internal energy utilization systems based on the principle of zero-waste circularity. This system ensures that every waste stream is converted into economically valuable products without leaving any residue, thus not only reducing emissions and environmental burdens but also expanding the diversification of green energy and chemical products. The initial stage begins with a pre-treatment process that involves drying and homogenizing solid biomass to increase reaction efficiency in the subsequent conversion unit. The EFB fraction is then directed to a fast pyrolysis unit at 500–600°C to produce synthesis gas (syngas) and biochar. The resulting synthesis gas is purified and then converted through Fischer–Tropsch Synthesis (FTS) into Sustainable Aviation Fuel (SAF), naphtha, and renewable diesel, while the biochar functions as a soil amendment and long-term carbon sink.

Meanwhile, the PKS fraction is processed through partial gasification to produce additional synthesis gas with a higher hydrogen-to-carbon (H/C) ratio, thereby improving the quality of the syngas used in the FT process. This process also produces high-quality biochar that can be used as a solid fuel or carbon fertilizer, strengthening the system's function in closing the biomass carbon cycle.

The POME (liquid waste) fraction is processed through a two-stage anaerobic digestion (AD) process, namely acidogenesis and methanogenesis, to produce biogas and digestate. The resulting biogas is then purified into biomethane (CH_4 >95%), which is used as fuel in the Combined Heat and Power (CHP) system to meet internal energy needs and as an additional raw material in the gas reforming process to increase SAF yield. The remaining liquid from fermentation, known as digestate, is used as a biofertilizer, ensuring that all waste fractions are utilized productively.

The synergy between material flow and internal energy makes this system technically and thermodynamically efficient. The heat generated from the pyrolysis unit is reused for the biomass drying process and heating the FT reactor, thereby reducing external energy requirements by up to 30%. With a closed-loop system design, no residual streams are wasted, as all by-products are reused as energy, chemicals, or organic fertilizer. The combination of conversion efficiency, energy recycling, and full utilization of all waste fractions makes this configuration a concrete representation of a technically optimal biorefinery system aligned with the principles of a sustainable circular economy. The mass balance results in table 1 are shown in the following table (Aspen Plus-based simulation data and reference literature from (IRENA 2022):

Table 1 Mass balance of PKS waste conversion in the integrated biorefinery model

Waste Fraction	Input (tons/day)	Main Products	Output (tons/day)	Conversion Efficiency (%)
EFB	150	Syngas → SAF	45	30,0
PKS	100	Biochar + Gas	38	38,0
APPLE	200	Biogas + Biofertilizer	180	90,0
Total	**450**	**SAF + Co-products**	**263**	**58,4 (overall)**

Mass balance calculations are carried out with reference to the basic mass conservation equation:

$$\sum \mathrm{M_{in}} = \sum \mathrm{M_{out}} + \sum \mathrm{M_{loss}}$$

Where M in is the mass of raw materials (EFB, PKS, POME), M out includes all products and co-products, and M loss is the mass loss due to evaporation and minor gas conversion (<2%). With Mloss (mass loss due to evaporation and minor gas residue) less than 5% of the total input. In terms of energy, the comparison between the output energy (SAF products, biogas, and biochar) and input energy (heating, electricity, and compression) shows a net energy efficiency of 72%, with a total output energy of 36.8 GJ/ton of waste and an input energy of 74 GJ/ton. This value is converted to the Energy Return on Investment (EROI) parameter using the equation:

$$EROI = \frac{E_{\text{output}}}{E_{\text{input}}}$$

Information:

- E output = total energy produced from main and by-products (GJ/ton waste)
- E input = total energy used for process operations (GJ/ton of waste)

Based on the results of thermodynamic simulations and energy balances of the integrated biorefinery model, the following data were obtained:

- The total energy output from the main products (SAF, biogas/biomethane, and biochar) is 36.8 GJ/ton of waste.
- Energy input for heating, electricity, and compression is 7.4 GJ/ton of waste

Thus, the EROI value can be calculated as follows:

$$\mathrm{EROI} = \frac{36,8}{7,4} = 4,97$$

This means that every 1 unit of energy invested into the system produces 4.97 net units of energy back, indicating that this system is thermodynamically efficient and produces positive energy.

Clean energy efficiency (or Narcissus) can also be expressed in percentage form with the formula:

$$\eta_{energi} = \left(\frac{E_{output} - E_{input}}{E_{output}}\right) \times 100\%$$

$$\eta_{energi} = \left(\frac{36,8 - 7,4}{36,8}\right) \times 100\% = 79,9\%$$

However, if the efficiency is calculated against the total direct energy conversion used in the process (without taking into account internal recycled heat), the conservative value used in this study is 72%, in accordance with the adjusted results based on dynamic thermal simulations using Aspen Plus V14.

With an EROI of 4.97 and a net energy efficiency of around 72–80%, this integrated biorefinery system is classified as a sustainable energy system. Theoretically, the minimum economic feasibility threshold for a bioenergy system is EROI ≥ 3 (Hall et al., 2014; IRENA, 2022). Values above this threshold indicate that the biorefinery design is not only technically optimal but also energetically robust for industrial-scale operation.

The technical optimization of this configuration is achieved through three main synergies. First, inter-process unit synergy, where waste heat from the pyrolysis unit is used to dry biomass and maintain the FT reaction temperature, thereby reducing external energy requirements by up to 25%. Second, internal energy synergy, where biomethane from POME fermentation is utilized for the reactor heating system, resulting in a self-sufficient system that does not rely on fossil fuels. Third, environmental synergy, where biochar acts as a carbon sink and soil fertilizer, contributing to CO_2 emission reductions while increasing oil palm plantation productivity.

The integration of these three synergies creates a biorefinery system with stable technical performance, high conversion efficiency, and no unused waste streams. This model not only represents technological innovation in palm oil industry waste processing but also supports the national agenda towards decarbonizing the energy sector and a sustainable bioeconomy. The achieved technical and energy efficiencies provide a strong basis for the financial verification phase through Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PP) analyses. Thus, this integrated biorefinery configuration can be positioned as a prototype of a green industry that is simultaneously technically, economically, and ecologically feasible.

Co-products Portfolio and Financial Sustainability Analysis

The analysis shows that the Zero-Waste Palm Oil biorefinery model produces a broad portfolio of co-products with high economic value beyond the primary production of Sustainable Aviation Fuel (SAF). Based on the mass and energy balance calculations (table 2), each ton of crude palm oil (CPO) and its derivative waste can be converted into 0. 18 tons of SAF, 0 12 tons of biofertilizer, 0.05 tons of biochar, 0.03 tons of bioplastic precursor, and 0.02 tons of green surfactant. Each product has a different relative economic value, depending on the domestic and export market prices in 2024 as referenced from the Ministry of Agriculture (2024), the World Bank Commodity Outlook (2024), and the International Energy Agency (IEA 2023) report. Table 2 shows an estimated co-product portfolio and its economic value per ton of production. With an average SAF price of USD 1,100/ton and co-product prices varying between USD 250–1,200/ton, the revenue contribution from derivative products reaches approximately 42. 6% of the total output value. This figure indicates that product diversification substantially strengthens the biorefinery's revenue structure and reduces dependence on the volatile aviation fuel market. Economic results show that SAF remains the primary revenue generator, but co-products play a crucial role in strengthening cash flow stability and long-term profitability. Products such as biofertilizers and biochar offer high margins due to their low production costs. At the same time, bioplastic precursors and green surfactants provide export opportunities for the rapidly growing global green chemistry industry (CAGR >10%, according to the (OECD Bioeconomy Report 2024). To assess investment feasibility, a financial analysis is performed using Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PP). The calculation follows the standard formula:

- IRR = r which makes NPV = 0
- Payback Period = number of years until the cumulative value of net cash flow = initial investment

$$NPV = \sum_{t=0}^{n} \frac{R_t - C_t}{(1+r)^t}$$

- Rt = revenue in year t, Ct = total operating costs in year t, r = discount rate (assumed 10%), and n = project Life (20 years).

The basic assumptions used include a total initial investment (CAPEX) of USD 220 million, average annual revenue of USD 56 million, annual operating costs of USD 28 million, and selling prices of SAF and co-products as per Table 2.

The calculation results are presented in Table 3. The positive NPV and IRR above the regional hurdle rate indicate that this biorefinery project is financially viable and offers competitive investment margins for the renewable energy sector in Southeast Asia. The 6. 2-year payback period demonstrates good capital efficiency for biomass-based projects, which typically have payback periods of 8–10 years. Sensitivity results also show that

Table 2 Derivative Product Portfolio and Relative Economic Value of Zero-Waste Palm Oil Biorefinery Model

No	Types	Production Ratio (tons/tons of CPO input)	Selling Price (USD/ton)	Economic Value per Ton of CPO (USD)	Income Share (%)
1	Sustainable Aviation Fuel (SAF)	0. 18	1,100	198. 0	57. 4
2	Biofertilizer	0. 12	250	30. 0	8. 7
3	Biochar	0. 05	450	22. 5	6. 5
4	Bioplastic precursor	0. 03	1,200	36. 0	10. 4
5	Green surfactant	0. 02	1,000	20. 0	5. 8
	Total	—	—	**306. 5**	**100. 0**

Table 3 Financial Indicators of the Zero-Waste Palm Oil biorefinery Model

Parameter	Mark	Unit	Information
Initial Investment (CAPEX)	220,000,000	USD	Project value
Average Annual Income	56,000,000	USD	SAF + co-products
Annual Operating Expenses (OPEX)	28,000,000	USD	Including maintenance
Net Present Value (NPV)	68,200,000	USD	r = 10%, n = 20 years
Internal Rate of Return (IRR)	17. 6	%	On hurdle rate regional
Payback Period	6. 2	Year	Break-even point of investment
SAF Price Sensitivity (±10%)	IRR: 13. 9–19. 8	%	Still economically viable
FFB Price Sensitivity (±15%)	IRR: 14. 5–17. 2	%	Stable against input fluctuations

a 10% decrease in SAF prices or a 15% increase in feedstock costs does not significantly alter the project's financial feasibility. This strong financial performance is heavily influenced by the contribution of co-products as a revenue buffer against energy market fluctuations. In a macroeconomic context, this multi-segment revenue structure makes the model more resilient to global commodity price uncertainty and exchange rate volatility. Thus, the Zero-Waste Palm Oil biorefinery model is not only ecologically sustainable through emission reduction and total waste utilization, but also financially sustainable by generating a positive NPV, high IRR, and long-term revenue stability. Overall, these findings strengthen the position of the palm oil biorefinery as a circular economy model capable of converting industrial residues into a portfolio of high-value green energy and chemicals. The successful integration of technology, product diversification, and financial efficiency makes this model worthy of adoption as a national policy reference in the transition to a low-carbon bioeconomy based on domestic resources.

Greenhouse gas emission mitigation based on Life Cycle Assessment (LCA)

LCA Methodology and System Boundaries

Life Cycle Assessment (LCA) was applied to assess the environmental performance of the model-integrated biorefinery based on palm oil waste in producing Sustainable Aviation Fuel (SAF) and its derivative products of economic value (co-products). The study was conducted with a cradle-to-tank approach, encompassing all stages from palm oil waste collection to distribution-ready SAF production. The distribution and fuel combustion phases in aircraft engines are not included in the system boundaries because this study focuses on process conversion efficiency and potential emission mitigation along the production chain.

Table 4 shows the basic assumptions used, including a national electricity emission factor of 0.79 kg CO_2-eq/kWh (ESDM 2023), a thermochemical conversion efficiency of the HEFA process of 78%, and an energy allocation method between products that follows the proportion of actual energy output. The system operates on the principle of zero waste, using the solid residue as internal biomass fuel, while the POME-treated water is reclaimed and reused in the system.

Life cycle emission calculations show that the system-integrated biorefinery palm oil waste-based fuel produces total emissions of 17. 3 g CO_2-eq/MJ, which is significantly lower than conventional jet fuel (Jet A-1) of 89 g CO_2-eq/MJ. This value is obtained through the integration of Life Cycle Inventory (LCI) from each stage of the process, including waste collection, pre-treatment (pretreatment), HEFA conversion, and the SAF purification stage. With the following formula:

$$\text{Emisi total (g CO}_2\text{-eq/MJ)} = \frac{\sum(E_i \times FE_i)}{E_{produk}}$$

E_i = energy consumption per process (MJ, electricity or heat)

FE_i = emission factor of each energy source (kg CO_2-eq/MJ)

E_{produk} = total energy output SAF (MJ)

With the assumption data:

- Total electricity consumption: 0.19 kWh/kg SAF (≈0.68 MJ/kg).
- Indonesia's electricity emission factor: 0 79 kg CO_2-eq/kWh (ESDM 2023).
- Heat energy (internal biomass) is considered carbon neutral because it comes from biomass residue.
- Additional process emissions (H_2, catalyst, transport): ±6. 4 g CO_2-eq/MJ. So the total emissions are:

$$(0,68\ \text{MJ/kg} \times 0,79\ \text{kg CO}_2\text{-eq/kWh} \times 0,277) + 6,4 \approx 17,3\ \text{g CO}_2\text{-eq/MJ}$$

The overall calculation results in an emission value of 17. 3 g CO_2-eq/MJ, in line with the model results. GREET 2022 and ICCT 2023 reported a range of 15–25 g CO_2-eq/MJ for waste-based HEFA fuels. When compared with the LANE baseline of 89 g CO_2-eq/MJ, this model shows a reduction in greenhouse gas emissions of 82 g CO_2-eq/MJ. 6%, calculated through the relative reduction formula (89−17 3)/89×100 89 - 17 3) / 89 \ × 100(89−17) 3)/89×100. This figure exceeds the minimum limit of 70% required by Renewable Energy Directive II (RED II) of the European Union, indicating that the palm oil waste-based biorefinery system theoretically meets international sustainability criteria.

The energy value of the SAF product is recorded at 41. 7 MJ/kg, which is calculated based on the lower Heating Value(LHV) of the hydrocarbon fraction resulting from the HEFA process based on feedstock high in saturated fatty acids (C_{16}–C_{18}) such as palm oil, using the LHV calculation formula as follows:

$$\text{LHV} = 33,86C + 144,4(H - O/8)$$

(in MJ/kg, based on elemental weight %)

For the HEFA fraction with the composition: C=85%, H=14%, O=1%, then LHV ≈ 41. 7 MJ/kg. The value of 41. The 7 MJ/kg obtained from the Lower Heating Value (LHV) of the hydrocarbon fraction in the HEF process shows consistent results with the GREET Model 2022 simulation and the IATA Sustainable Fuel 2023 report. This consistency shows that the specific energy of SAF from palm oil waste is practically equivalent to fossil-based Jet A-1, which has an energy range of 42–44 MJ/kg. From a mass balance perspective, the biorefinery system demonstrated high conversion efficiency, with approximately 64% of the dry mass of the waste being successfully converted into economically valuable products. This proportion comprised 42% of the primary SAF fraction, along with by-products in the form of bio-naphtha and bio-LPG. This ratio was obtained through HEFA process simulations that considered the lignocellulose content of empty fruit bunches, shells, and POME. These results align with studies by Lestari et al. (2022), which recorded a SAF yield of 40–44% from solid palm oil waste, as well as findings by Zhou et al. (2021), who reported total conversion efficiencies of 60–65% for lignocellulosic feedstock in a similar process.

Thus, all the calculation results above are derived from a combination of LCA modelling based on GREET 2022 and Ecoinvent v3. 9, national emission factors (ESDM, 2023), and validation against standardsLANE And ROW IIOverall, these values demonstrate strong methodological consistency and empirical relevance, confirming that a palm oil waste-based biorefinery system is capable of providing substantial environmental benefits while producing sustainable energy products with technical performance equivalent to conventional fuels.

Zero-Waste Model Total GHG Emission Mitigation

The results of the Life Cycle Assessment (LCA) calculations indicate that applying the Zero-Waste biorefinery model to the palm oil mill waste processing system significantly reduces total greenhouse gas emissions compared to the baseline scenario (conventional waste processing). This model includes the integration of liquid waste (POME) utilization into biogas and Sustainable Aviation Fuel (SAF), as well as the conversion of solid waste such as empty fruit bunches (EFB) and shells into biochar and solid fuel (pellets).

The results in the table 6 that the implementation of the Zero-Waste biorefinery model has consistently reduced greenhouse gas emissions throughout all stages of the production Life cycle. The largest reduction in emissions occurred in the processing of liquid waste (POME), with a mitigation rate of 88. 8%. This achievement is due to the elimination of the main source of methane (CH_4), a gas with a global warning potential 28 times higher than CO2, through biological

Table 4 Main parameters and limitations of the LCA system

Assessment Components	Core Values / Assumptions	Source / Notes
Systems approach	Cradle-to-Tank	ISO 14040/44 Adaptation
Main raw materials	Empty bunches, shells, POME	PKS waste
HEFA conversion efficiency	78%	Pilot scale test
National electricity emission factor	0. 79 kg CO_2-eq/kWh	ESDM (2023)
Energy allocation scheme	Based on the proportion of energy output	RED II Compliant
Waste system	Zero waste (reuse & recycle)	Adaptive design
Production capacity	50,000 tons of SAF/year	Medium factory assumption
System limits	Waste collection → SAF Products	Does not include final combustion

Table 5 LCA result and efficiency system

Evaluation Parameters	Mark	Unit	Benchmark (LANE/RED II)	Information
Total Life cycle emissions	17,3	g CO_2-eq/MJ	< 89 (LANE)	Meet the threshold
Reduction of GHG emissions	82,6	%	≥ 70 (RED II)	Exceeding EU standards
Process energy efficiency	78	%	70–75 (global literacy)	Efficient
SAF yield from waste	42	% dry mass	-	High for lignocellulosic feedstock
SAF energy allocation: co-products	65: 35	%	-	According to the output proportion
SAF product energy	41,7	MJ/kg	42–44 (Jet A-1)	Equal quality
Solid residue reduction	95	%	-	Almost zero waste

Table 6 GHG Emission Mitigation Analysis Based on Life Cycle Assessment (LCA)

Life Cycle Stage	Baseline Emissions (kg CO_2-eq/ton FFB)	Emisi Model Zero-Waste (kg CO_2-eq/ton TBS)	Mitigation (%)	Main Description
Collection and transportation of fresh fruit bunches	80	72	10,0	Route efficiency and biodiesel use
Oil extraction process	210	165	21,4	Waste heat utilization for pre-heating
Liquid waste treatment (POME)	610	68	88,8	Methane is converted into biogas and SAF
Solid waste processing (EFB, shells)	460	215	53,3	Biochar and pellet production; carbon sequestration
Additional energy from the biorefinery process	270	210	22,2	Integration of a biogas-fired boiler
Total	**1. 630**	**730**	**≈ 72,4%**	**Reduction in total GHG emission intensity**

conversion to biogas and Sustainable Aviation Fuel (SAF). Before the intervention, POME was a dominant contributor to the palm oil industry's carbon footprint, contributing approximately 37% of total emissions from conventional systems. In other words, the success of POME processing not only reduces direct emissions from the anaerobic decomposition process but also converts hazardous waste into a clean energy source that can replace fossil fuels. The stage with the second-highest mitigation impact is solid waste processing, particularly empty fruit bunches (EFB) and shells. The process of converting lignocellulose into biochar and biomass pellets yields a mitigation efficiency of 53. 3%. Biochar functions as a long-term carbon sink in the soil, creating a negative emission effect. At the same time, the pellets are used as a coal substitute fuel, resulting in significantly reduced emissions in the industrial energy system. Thus, this stage plays a dual role: reducing emissions from the waste disposal process and simultaneously providing carbon credits through fossil fuel substitution.

Nevertheless, the Life Cycle Inventory (LCI) analysis shows that the hydrotreatment unit in SAF production is the most significant emissions hotspot in the biorefinery configuration. This unit contributes approximately 34% of total system emissions, primarily due to its high thermal energy requirements and the use of hydrogen in the oil upgrading process. However, when credit allocations from conventional jet fuel substitution are taken into account, the net impact on total system emissions is significantly lower. This means that while the hydrotreatment unit is directly energy-intensive, its systemic contribution to mitigation remains positive because it produces low-carbon fuels that replace high-emission fossil fuels. Furthermore, the drying and pelletizing processes of solid waste have also been identified as significant contributors to indirect emissions. This is due to the reliance on grid-based electricity, which is still predominantly coal-fired in most operating areas. Implementing a biogas energy recovery system, for example, through a cogeneration unit, has the potential to reduce indirect emissions by up to 27%. This energy integration not only increases system efficiency but also strengthens the circular nature of energy in the Zero-Waste model, where heat, gas, and biomass residue are reused in the production process.

Systemically, the success of the Zero-Waste GHG mitigation model is supported by three main mechanisms. First, the elimination of methane (CH_4) release from POME through the use of renewable energy technologies directly reduces the most destructive emissions in the palm oil system. Second, converting solid residues into value-added products like biochar and pellets not only reduces the waste load but also acts as a carbon storage agent and substitutes for fossil fuels. Third, the integration of circular energy (energy looping) between the biogas unit, boiler, and thermochemical process reduces dependence on external energy sources and improves the system's overall carbon balance.

Thus, the Zero-Waste model is not merely a technical innovation in waste management; it represents a paradigm shift in the palm oil industry toward a low-carbon bioeconomy. This approach demonstrates that waste can be repositioned as a strategic resource to support Indonesia's Net Zero Emissions agenda by 2060. Furthermore, these results provide an empirical basis for policymakers to encourage the implementation of green economy incentives, carbon certification, and the integration of biorefinery systems into the national palm oil supply chain. Conceptually, this model emphasizes that sustainability does not depend on production reductions, but on the reconstruction of value and energy systems within the production process itself.

Market Validation and Policy Framework for Waste-Based SAF Adoption

Compliance and Effectiveness of Sustainability Certification Frameworks

The integrated Palm Oil Mill biorefinery (IPOMB) model demonstrates a high level of compliance with the key principles and criteria of the two most influential global sustainability certification schemes: the Roundtable on Sustainable Palm Oil (RSPO) and the international sustainability and carbon certification

(ISCC). Based on the analysis results of the process and output of this system, it is known that all fractions of palm oil waste have been successfully converted into Sustainable Aviation Fuel (SAF), biogas, biochar, and organic liquid fertilizer. This total waste conversion process meets RSPO principles. Criterion 7. 7which emphasizes "The unit of certification should have a system to identify, protect or rehabilitate areas of peat, areas of high carbon stock, and other land of conservation value within the management boundary." (RSPO 2023). At the same time, this system is also aligned with the ISCC Principle, which states that "sustainable biomass production must ensure the conservation of natural resources, including land, water, and air" (ISCC 2024).

Implementation of the mechanism closed-loop system: The biorefinery produces a nearly perfect circulation of energy and materials, with very low emissions. The use of POME as a feedstock for biogas and SAF reduces methane emissions by up to 88%. 8%, as verified through analysis. *Life Cycle Assessment* (LCA). These results support RSPO compliance Criterion *7. 8*which demands systematic efforts to "reduce greenhouse gas emissions and increase energy efficiency in palm oil production activities", as well as meet ISCC Principle who wrote *"*Biomass is not produced on land with high biodiversity value. Biomass is not produced on land with high carbon stock. Biomass is not produced on peatland.*"* (ISCC 2024). Thus, from an environmental and energy efficiency perspective, IPOMB has demonstrated the potential for substantive compliance with the two certification frameworks.

Apart from the technical dimension, IPOMB also has the administrative readiness to support product traceability. An integrated supply chain system from palm oil mills to SAF production enables the implementation of the scheme. *Chain of custody, which* is compatible with both global certifications. In the context of RSPO and ISCC, there are two main mechanisms for ensuring sustainability validity, namely the mass balance approach and *segregation*. The analysis shows that the mass balance approach *is* the most effective validation strategy for integrated biorefinery systems. This approach allows the mixing of certified and non-certified raw materials in a single production flow, provided the proportions and volumes of each can be calculated and reported transparently. This strategy is in line with the RSPO Supply Chain Certification Standard, which states that the mass balance supply chain model allows each participant within the supply chain to demonstrate their commitment to RSPO certified oil palm production. The mass balance system allows for mixing of RSPO and non-RSPO certified oil palm products at any stage in the supply chain, provided that overall site quantities are controlled (RSPO 2023).

On the contrary, the approach of segregation requires complete separation of certified and non-certified raw materials throughout the supply chain. While this approach provides a higher level of credibility in the eyes of end consumers, its application in a biorefinery model like IPOMB would lead to operational inefficiencies, as all waste raw materials originate from a single, integrated, and documented palm oil industry supply chain. Within this framework, the ISCC Chain of Custody System uses mass balance, recognized as a valid method for maintaining sustainability integrity, as long as material flow calculations are carried out accurately and verified through annual audits (ISCC 2024). Thus, the application of mass balance with enhanced traceability is a strategic choice that balances economic efficiency, administrative validity, and ecological credibility. By implementing this strategy, SAF products based on palm oil mill waste can gain sustainability recognition in the international market without sacrificing logistical efficiency or certification costs. This approach strengthens Indonesia's position as a supplier of sustainable bioenergy with low emissions intensity and high supply chain transparency. Going forward, the integration of a digital-based carbon audit system and harmonization of national and global standards will be key to expanding market access for Indonesian SAF under the RSPO and ISCC certification regimes. Thus, this integrated biorefinery model serves not only as a green technology innovation but also as a strategic instrument for achieving sustainability legitimacy in the governance of the global palm oil industry.

Market Implementation Strategy and Policy Recommendations

The results of the study show that the market implementation strategy is a key element in the successful adoption of the model. Zero-Waste palm oil biorefinery this approach requires a comprehensive integration of economic value and environmental sustainability so that innovative technologies for converting palm oil waste into sustainable fuels and value-added derivative products can operate on a stable commercial scale. One of the most promising strategies is developing partnerships. Off-take between producers of Sustainable Aviation Fuel (SAF) and domestic and international airlines. Through long-term contracts, this scheme provides market security for manufacturers and supply certainty for the aviation industry, which is facing global pressure to reduce carbon emissions in line with standards. Carbon Offsetting and Reduction Scheme for International Aviation (LANE).

In addition to market guarantees, the effectiveness of the biorefinery model can also be strengthened by implementing premium prices for by-products (co-products) that are certified bio-based. Products such as biofertilizers, bioplastic precursors, green surfactants, and biochar have high selling value in the global market, especially after obtaining internationally standardized certifications such as International Sustainability and Carbon Certification (ISCC Plus) or Roundtable on Sustainable Biomaterials (RSB). With this approach, palm oil waste derivative products are seen not only as by-products but also as superior commodities that contribute to the green chemical industry portfolio (green chemicals). Financial analysis shows that the combination of contracts of take and premium pricing schemes can create more stable cash flows, reduce market risks, and increase investment feasibility compared to conventional business models that still rely on crude CPO exports. In a policy context, these results underscore the need for a synchronized regulatory framework across the energy, environmental, and industrial sectors to ensure an effective transition to biorefinery. The government needs to formulate fiscal and non-fiscal incentives that directly encourage investment in palm oil waste conversion technology into SAF and its derivatives. Fiscal support could take the form of tax holidays, income tax relief, and green financing schemes through financial institutions that prioritize low-carbon projects. This approach not only reduces initial investment risk but also accelerates the diffusion of clean technologies in the agro-industrial sector. On the demand side, the renewable fuel blending mandate policy in the aviation sector can serve as a key instrument for shaping the domestic market. The gradual implementation of a mandatory SAF blend of 2–5% until 2030 will create a stable market and underscore Indonesia's commitment to a clean energy transition. To ensure ecological sustainability, a zero-discharge waste management policy should be strengthened by regulations that mandate converting liquid waste, Palm Oil Mill Effluent (POME), into biogas, organic fertilizer, or secondary fuel. Such policies not only reduce methane emissions but also serve as a crucial prerequisite for sustainability-based export certification, which is now a global market standard.

Furthermore, institutional consolidation at the supply chain level is a crucial supporting factor. Regional governments, along with industry associations such as GAPKI and APROBI, can encourage the formation of biorefinery clusters that integrate plantations, palm oil mills, and advanced processing facilities into a single, coordinated logistics system. This approach strengthens economies of scale, reduces transaction costs, and opens up opportunities for synergy across business actors.

With a combination of adaptive market strategies and progressive public policies, the transformation of the palm oil industry toward a low-emission production system will become not just a technological discourse but a national strategic agenda. The zero-waste biorefinery presents a new paradigm that positions waste as a resource of economic value and an instrument of Indonesia's green diplomacy in the global energy market.

CONCLUSION

From the research results above, it can be concluded that the integrated zero-waste palm oil biorefinery design developed in this study has successfully utilized all fractions of palm oil mill waste—EFB, PKS, and POME—into a portfolio of economically valuable products, leaving no residue behind. Through the integration of thermochemical (pyrolysis–gasification–FTS) and biochemical (anaerobic digestion) processes, this system achieves a mass conversion efficiency of 58%. 4%, a net energy efficiency of 72%, and an EROI value of 4.97, far above the minimum feasibility threshold of a global bioenergy system (EROI ≥ 3).

From an environmental perspective, the implementation of this model resulted in a 72. There is a 4% reduction in greenhouse gas emissions, with the most significant mitigation (88.8%) occurring in the treatment of POME wastewater through the conversion of methane into biogas and SAF. The total Life cycle emissions of the SAF produced were 17. 3 g CO_2-eq/MJ, exceeding the CORSIA (<89 g CO_2-eq/MJ) and RED II (>70% reduction) sustainability standards. These results confirm that this biorefinery system is not only zero-waste in material terms, but also low-carbon in energy terms.

Technically, the success of this model is supported by three main synergies: (1) thermal synergy between process units, where pyrolysis waste heat is reused for the FTS reactor and biomass drying; (2) internal energy synergy, where biomethane from POME is used for the Combined Heat and Power system; and (3) environmental synergy, with the use of biochar as a carbon sink and soil fertilizer. These three synergies make the system energy self-sufficient, zero-residue, and operationally economical. With a cost and revenue structure that produces a positive NPV (USD 68.2 million), an IRR of 17. With a 6% rate and a Payback Period of 6.2 years, this model can be categorized as a superior sustainable system from a technical, financial, and environmental perspective. Thus, the integrated zero-waste biorefinery is not only a technological innovation, but a concrete green industrial model that converts waste into energy and is carbon negative. This design is worthy of being used as a national blueprint for the decarbonization of the palm oil industry and as a globally competitive circular economy model.

Although the integrated Zero-Waste Palm Oil biorefinery design demonstrates promising technical and financial performance, this study has several limitations that require attention during implementation. First, the mass and energy balance simulations used are still based on the assumption of ideal laboratory process conditions and secondary data (Aspen Plus and industry literature). Therefore, operational variability in the field, such as fluctuations in biomass moisture content, POME feed quality, and actual conversion efficiency, has the potential to degrade the system's performance at an industrial scale. Second, the financial analysis was conducted using a static cash flow approach and did not take into account the dynamics of global energy prices, inter-unit logistics costs, and potential exchange rate volatility that could affect the long-term NPV and IRR. Third, socio-ecological aspects such as local community acceptance, biochar waste management, and land footprint have not been discussed in depth. Therefore, field validation through the construction of a pilot plant is a crucial step to empirically ensure the system's technical reliability and economic feasibility.

From a technical perspective, it is recommended to develop a demonstration-scale pilot plant with a capacity of 50–100 tons of waste per day in an integrated palm oil industrial area in Sumatra or Kalimantan to realistically test energy efficiency, reactor stability, and integrated raw material logistics. This system needs to adopt biogas and biomethane-based cogeneration (CHP) technology to achieve energy efficiency above 80% and ensure full energy independence. Implementation of a digital mass balance monitoring system is also necessary to ensure material traceability, thermal efficiency, and compliance with RSPO and ISCC sustainability standards. Furthermore, the use of biochar as a carbon crediting mechanism can provide additional revenue for biorefinery operators while strengthening Indonesia's position in the global carbon economy market. Strategic collaboration with universities and energy research institutions needs to be expanded to develop local catalysts and optimize the FTS upgrading process, so that SAF yield and by-product added value can be continuously increased.

From a policy perspective, the government needs to establish a mandatory “Zero-Discharge Palm Oil Mill” regulation as a condition for the renewal of PKS operating permits starting in 2030, to ensure widespread adoption of this sustainable biorefinery model. Support for green fiscal incentives, such as tax holidays, carbon credit trading, and green financing guarantees, is crucial to lowering initial investment barriers. Furthermore, a national SAF mix mandate of 2–5% by 2030 in the aviation sector needs to be implemented immediately to create a stable and attractive domestic market for investors. The government is also advised to establish a national palm oil biorefinery cluster, integrating plantations, palm oil mills, and bioenergy facilities within a coordinated industrial ecosystem to improve logistics efficiency and export competitiveness. At the global level, accelerating the alignment of RSPO, ISCC, and RSB standards within the Indonesia Sustainable Bioenergy Standard (ISBS) framework is necessary for palm oil waste-based SAF products to comply with European Union and East Asian sustainability regulations.

With a simultaneous approach between technology strengthening and policy support, the integrated Zero-Waste biorefinery model has the potential to become a milestone in the structural transformation of the Indonesian palm oil industry, shifting from a raw commodity-based sector to a globally competitive, low-carbon, energy-efficient, and socially inclusive circular economy.

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