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DECARBONISING THE PALM OIL VALUE CHAIN: A REVIEW OF SUSTAINABILITY CERTIFICATIONS, POLICY ALIGNMENT, AND TECHNOLOGICAL READINESS FOR NET-ZERO TARGETS

DESCARBONIZANDO A CADEIA DE VALOR DO ÓLEO DE PALMA: UMA REVISÃO DAS CERTIFICAÇÕES DE SUSTENTABILIDADE, ALINHAMENTO DE POLÍTICAS E PRONTIDÃO TECNOLÓGICA PARA METAS DE EMISSÕES LÍQUIDAS ZERO

DESCARBONIZACIÓN DE LA CADENA DE VALOR DEL ACEITE DE PALMA: UNA REVISIÓN DE LAS CERTIFICACIONES DE SOSTENIBILIDAD, LA ALINEACIÓN DE POLÍTICAS Y LA PREPARACIÓN TECNOLÓGICA PARA LOGRAR OBJETIVOS DE CERO EMISIONES NETAS

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ABSTRACT

The global greenhouse gas footprint of the palm oil sector is substantial, making the decarbonisation of its entire value chain an urgent priority. This study aims to critically review the effectiveness of sustainability certifications, policy frameworks, and technological innovations in supporting net-zero targets within the palm oil sector. Employing a qualitative literature review approach, the research synthesises findings from peer-reviewed journals, policy reports, and institutional publications dated between 2015 and 2025. Data collection was conducted through systematic searches in databases such as Scopus, Web of Science, and ScienceDirect, selecting 80 relevant studies based on strict inclusion criteria related to emissions data, policy analysis, and technological readiness. Thematic analysis was applied to interpret and integrate the collected literature. Results indicate that sustainability certifications like RSPO, ISPO, and MSPO contribute to measurable emissions reductions, yet face challenges related to enforcement and regional disparities. Policy alignment is fragmented, with national targets often undermined by inconsistent implementation and overlapping regulatory mandates. Technological readiness varies significantly, with large-scale producers adopting methane capture and precision agriculture technologies, while smallholders experience limited access due to financial and technical constraints. The study concludes that coordinated integration of certification schemes, robust policy frameworks, and equitable technology dissemination is essential to accelerate decarbonisation in the palm oil value chain. Future research should explore scalable support mechanisms for smallholders and investigate innovative policy models to enhance sector-wide climate action.

Keywords: Palm oil decarbonisation. Sustainability certifications. Policy alignment. Technological readiness. Qualitative literature review.

RESUMO

A pegada global de gases de efeito estufa do setor de óleo de palma é substancial, tornando a descarbonização de toda a sua cadeia de valor uma prioridade urgente. Este

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estudo visa revisar criticamente a eficácia das certificações de sustentabilidade, marcos políticos e inovações tecnológicas no apoio às metas de emissões líquidas zero no setor de óleo de palma. Empregando uma abordagem qualitativa de revisão bibliográfica, a pesquisa sintetiza resultados de periódicos revisados por pares, relatórios de políticas e publicações institucionais datados entre 2015 e 2025. A coleta de dados foi realizada por meio de buscas sistemáticas em bases de dados como Scopus, Web of Science e ScienceDirect, selecionando 80 estudos relevantes com base em critérios de inclusão rigorosos relacionados a dados de emissões, análise de políticas e prontidão tecnológica. A análise temática foi aplicada para interpretar e integrar a literatura coletada. Os resultados indicam que certificações de sustentabilidade como RSPO, ISPO e MSPO contribuem para reduções mensuráveis de emissões, mas enfrentam desafios relacionados à aplicação e disparidades regionais. O alinhamento de políticas é fragmentado, com metas nacionais frequentemente prejudicadas por implementações inconsistentes e mandatos regulatórios sobrepostos. A prontidão tecnológica varia significativamente, com produtores em larga escala adotando tecnologias de captura de metano e agricultura de precisão, enquanto pequenos produtores enfrentam acesso limitado devido a restrições financeiras e técnicas. O estudo conclui que a integração coordenada de esquemas de certificação, estruturas políticas robustas e disseminação equitativa de tecnologia é essencial para acelerar a descarbonização na cadeia de valor do óleo de palma. Pesquisas futuras devem explorar mecanismos de apoio escaláveis para pequenos produtores e investigar modelos de políticas inovadores para aprimorar a ação climática em todo o setor.

Palavras-chave: Descarbonização do óleo de palma. Certificações de sustentabilidade. Alinhamento de políticas. Prontidão tecnológica. Revisão qualitativa da literatura.

RESUMEN

La huella global de gases de efecto invernadero del sector del aceite de palma es considerable, lo que convierte la descarbonización de toda su cadena de valor en una prioridad urgente. Este estudio busca analizar críticamente la eficacia de las certificaciones de sostenibilidad, los marcos de políticas y las innovaciones tecnológicas para alcanzar los objetivos de cero emisiones netas en el sector. Mediante un enfoque cualitativo de revisión bibliográfica, la investigación sintetiza los hallazgos de revistas arbitradas, informes de políticas y publicaciones institucionales con fecha de 2015 a 2025. La recopilación de datos se realizó mediante búsquedas sistemáticas en bases de datos como Scopus, Web of Science y ScienceDirect, seleccionando 80 estudios relevantes con base en estrictos criterios de inclusión relacionados con datos de emisiones, análisis de políticas y preparación tecnológica. Se aplicó un análisis temático para interpretar e integrar la literatura recopilada. Los resultados indican que las certificaciones de sostenibilidad como RSPO, ISPO y MSPO contribuyen a reducciones mensurables de emisiones; sin embargo, enfrentan desafíos relacionados con la aplicación de las normas y las disparidades regionales. La alineación de las políticas está fragmentada, y los objetivos nacionales a menudo se ven socavados por una implementación inconsistente y la superposición de mandatos regulatorios. El grado de preparación tecnológica varía considerablemente: los grandes productores adoptan tecnologías de captura de metano y agricultura de precisión, mientras que los pequeños agricultores experimentan un acceso limitado debido a limitaciones financieras y técnicas. El estudio concluye que la integración coordinada de sistemas de certificación, marcos de políticas sólidos y la difusión equitativa de tecnologías son esenciales para acelerar la descarbonización en la cadena de valor del aceite de palma. Las investigaciones futuras deberían explorar mecanismos de apoyo escalables para los pequeños agricultores e investigar modelos de políticas innovadores para impulsar la acción climática en todo el sector.

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Palabras clave: Descarbonización del aceite de palma. Certificaciones de sostenibilidad. Alineación de políticas. Preparación tecnológica. Revisión cualitativa de la literatura.

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INTRODUCTION

Global efforts to mitigate climate change have intensified over the past decade, with a growing consensus among policymakers, scientists, and industry leaders on the urgent need to decarbonise critical economic sectors. The energy sector has long been the primary focus of global decarbonisation efforts, but increasing attention is now directed towards land-use change, agriculture, and forestry, which collectively contribute significantly to global greenhouse gas (GHG) emissions (Mori, 2023). Amid this backdrop, palm oil remains a subject of intense debate, reflecting its role as both a cornerstone of economic growth and an unfair accusations as being the sole major source of ecological degradation (Jamaludin et al., 2024).

Palm oil continues to rank among the most widely used edible oils globally, embedded in a wide range of products from food to biofuels, and its global demand continues to rise steadily (Koh et al., 2011). With a combined output surpassing 80% of global supply, Indonesia and Malaysia hold a dominant position in the palm oil production landscape, thus making the palm oil value chain a crucial area of focus in national development and climate mitigation strategies (Xin et al., 2022). Despite its economic significance, the environmental costs associated with palm oil production particularly the unfair accusations as being the sole cause of deforestation, peatland degradation, and biodiversity loss have drawn intense scrutiny from both domestic and international stakeholders (Petrenko et al., 2016). These impacts are further compounded by the carbon-intensive nature of land-use conversions involved in plantation expansion, which makes the palm oil value chain a high-priority target for decarbonisation interventions (Tan et al., 2024).

Initiatives aimed at cutting emissions in the palm oil industry are often implemented through sustainability standards like RSPO, ISPO, and MSPO (Rosdin et al., 2023). These frameworks aim to promote responsible practices across the value chain, from cultivation to processing and distribution, while also offering market-based incentives for compliance (Ramli et al., 2020). However, the effectiveness of these schemes in significantly reducing GHG emissions remains contested, due to varied enforcement mechanisms, uneven stakeholder participation, and issues related to traceability and transparency (Hadi et al., 2024).

Beyond certification, national and international policies have emerged to guide the alignment of the palm oil industry with climate goals. Global frameworks like the Paris Agreement and national commitments such as Indonesia's Nationally Determined

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Contributions (NDCs) under the United Nations Framework Convention on Climate Change (UNFCCC) underscore the importance of integrating sectoral decarbonisation into broader policy ecosystems (Clinton et al., 2024). Yet, the policy landscape remains fragmented, with conflicting signals between economic incentives for palm oil expansion and environmental imperatives to limit deforestation and reduce emissions (West et al., 2023). These inconsistencies present structural barriers to achieving net-zero emissions within the palm oil value chain, especially in the absence of coherent stakeholdersl coordination and enforcement (Tanaka et al., 2021).

In parallel, technological innovation is emerging as a critical enabler for decarbonising the palm oil industry. Innovations such as methane capture systems in palm oil mills, satellite-based monitoring for deforestation, and precision agriculture tools for optimising fertiliser use are increasingly cited as promising solutions (Hoo et al., 2017). Nevertheless, technological readiness across the value chain is uneven, often hindered by capital constraints, limited technical capacity among smallholders, and a lack of integration between research and practice (Irvin et al., 2020). In many cases, pilot projects demonstrate potential without scalable implementation strategies, resulting in technological stagnation and limited climate benefits (Garg et al., 2021).

Furthermore, the palm oil value chain involves a diverse constellation of actors smallholders, corporations, governments, NGOs, and consumers whose interests often diverge and at times conflict (Lusiana et al., 2023). Decarbonising such a complex value chain requires not only technical and regulatory solutions but also institutional alignment, participatory governance, and market transformation (Astari et al., 2025). The intersection of environmental objectives with socio-economic considerations makes this task particularly challenging in countries where palm oil plays a central role in rural livelihoods and national export earnings (Wardhani & Rahadian, 2021).

Despite the expanding body of research on palm oil sustainability, existing literature tends to focus on discrete aspects such as certification effectiveness, technological solutions, or policy critiques, often in isolation. There remains a gap in synthesised knowledge that critically examines the intersection of these dimensions through a decarbonisation lens, particularly one that aligns with net-zero targets set for mid-century (Ernanda et al., 2022). A more integrated understanding of how sustainability certifications, policy frameworks, and technological readiness converge or fail to converge is urgently needed to inform both strategic interventions and academic debates (Qing & Jin, 2023).

This article, therefore, aims to fill this gap by conducting a qualitative literature review that systematically explores how the palm oil value chain can be decarbonised through the synergistic application of sustainability certifications, policy alignment, and technological readiness. By mapping current knowledge, identifying thematic patterns, and highlighting critical challenges and opportunities, this study provides a conceptual foundation for integrated strategies that support national and global net-zero ambitions. Through this approach, the paper seeks to offer actionable insights for policymakers, industry actors, and researchers working at the intersection of sustainable agriculture and climate governance.

LITERATURE REVIEW

SUSTAINABILITY CERTIFICATIONS IN THE PALM OIL SECTOR

Certification schemes for sustainability have been created as essential tools to lessen the environmental effects associated with palm oil production. The most commonly acknowledged among these include the Roundtable on Sustainable Palm Oil (RSPO), the Indonesian Sustainable Palm Oil (ISPO), and the Malaysian Sustainable Palm Oil (MSPO) standards (Pratama, 2021). These certifications are designed to ensure that producers adhere to environmental, social, and economic sustainability criteria, including commitments to zero deforestation, peatland protection, and fair labour practices (Santika et al., 2021). However, evidence on their effectiveness in delivering genuine emissions reductions remains in needs for further research.

While RSPO-certified plantations often exhibit higher compliance with environmental safeguards compared to non-certified counterparts, studies highlight limitations in enforcement and traceability, particularly in downstream segments of the supply chain (Hirbli, 2018). ISPO, as Indonesia's mandatory standard, was introduced to improve regulatory compliance, but has faced criticism for weaker criteria and limited transparency in monitoring and evaluation (Kurnia et al., 2025). Similarly, MSPO is undergoing reform to enhance its alignment with global sustainability benchmarks, yet implementation gaps persist, particularly among smallholders (Lee et al., 2020).

Certification schemes often function more effectively as market access tools rather than comprehensive decarbonisation strategies. Many producers pursue certification to meet export requirements, rather than to reduce emissions as a climate mitigation goal (Harvey et al., 2025). Moreover, certification does not always guarantee the use of best available practices in carbon-intensive areas such as fertiliser use, land-clearing, or mill operations (Gallegos, 2024). These limitations suggest that while certifications offer a useful

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governance mechanism, their contribution to decarbonisation is conditional on complementary policy and technological frameworks (Kreibich & Hermwille, 2021).

CLIMATE POLICY AND GOVERNANCE ALIGNMENT

Effective decarbonisation of the palm oil sector depends heavily on coherent and enforceable policy frameworks at national and international levels. The climate pledges of Indonesia and Malaysia, particularly their Nationally Determined Contributions (NDCs) as part of the Paris Agreement, emphasize the importance of separating economic development from environmental harm (Djatmika et al., 2023). However, a persistent tension exists between climate goals and national development strategies, particularly those aimed at boosting palm oil exports and rural employment (Zamri et al., 2022).

National policies often suffer from fragmentation and institutional misalignment. For instance, while environmental ministries promote emission reductions and forest protection, agricultural and trade ministries frequently prioritise expansion and investment in palm oil production (Varkkey et al., 2018). This institutional dichotomy has been identified as a major barrier to integrated climate governance in the land-use sector (Naylor et al., 2019). Moreover, decentralisation of governance has further complicated policy coherence, with regional governments sometimes incentivising plantation expansion in contradiction to national emissions targets (Cisneros et al., 2021).

International pressure, particularly from the European Union, has prompted some reforms in sustainability governance. However, this external influence sometimes behaving as neo-colonial or trade-biased, leading to resistance from domestic actors and limiting the political legitimacy of climate-aligned policy reforms (Pedregal & Lukić, 2024). As such, successful decarbonisation will require locally legitimate policy instruments that align national interests with global climate obligations, rather than externally imposed compliance frameworks (Sutrisno, 2019).

Recent developments, such as Indonesia's carbon tax and results-based payments under the REDD+ scheme, represent steps towards aligning fiscal policy with climate objectives (Siregar, 2025). However, their application to the palm oil sector remains limited, and institutional capacity to monitor, verify, and enforce emissions reductions remains uneven (Gatto & Sadik-Zada, 2024). Overall, current policy regimes provide insufficient incentives or obligations for the industry to pursue a net-zero pathway in a systematic manner.

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TECHNOLOGICAL READINESS AND INNOVATION CAPACITY

Technology plays a pivotal role in enabling decarbonisation across the palm oil value chain. Emissions can be mitigated at multiple points, including land-use change prevention, fertiliser optimisation, mill processing improvements, and methane capture from palm oil mill effluent (POME) (Foong et al., 2021). Methane capture and biogas recovery systems, for example, have shown strong potential for reducing emissions at the mill level, though adoption rates remain low due to high capital costs and limited technical support (der Laan et al., 2017).

At the plantation level, precision agriculture technologies such as remote sensing, drone mapping, and variable-rate application systems can reduce input use and improve yield efficiency, thereby lowering indirect emissions (Balafoutis et al., 2017). However, technological diffusion is largely constrained by structural barriers, particularly among independent smallholders who lack access to finance, knowledge, and infrastructure. Without targeted public investment and supportive extension services, such innovations are unlikely to be scaled at the pace required for meaningful emissions reduction.

In addition, existing research and development efforts tend to be siloed and poorly integrated with policy or market structures. Pilot projects often demonstrate technical feasibility, but fail to reach commercial viability due to regulatory uncertainties, weak institutional coordination, or lack of demand-pull mechanisms (Abubakar & Ishak, 2024). The absence of reliable carbon accounting systems and digital infrastructure for traceability further inhibits technological progress in emissions tracking and verification.

The technological readiness of the palm oil industry must therefore be assessed not only in terms of availability but also in terms of scalability, affordability, and integration with broader sustainability frameworks. In this regard, technology alone cannot drive transformation; it must be embedded within a supportive ecosystem of policy, market incentives, and institutional capacity-building (Dominic & Baidurah, 2022).

Across these three dimensions certifications, policy, and technology the literature reveals common challenges: fragmented governance, inconsistent implementation, and limited systemic integration. While many studies have explored each dimension in isolation, few have synthesised them within a unified framework that addresses decarbonisation holistically. This lack of integration hampers the development of strategic pathways toward net-zero goals in the palm oil sector

METHOD

This study employs a qualitative research approach, specifically a qualitative literature review, aimed at gaining an in-depth understanding of the decarbonisation dynamics within the palm oil value chain through a critical analysis of relevant literature. The selection of this method is intended to identify emerging patterns, gaps, and conceptual trends in academic research and public policy concerning sustainability certifications, policy coherence, and technological readiness toward net-zero targets. The literature reviewed includes peer-reviewed scientific publications, institutional reports, policy documents, and articles from reputable international journals published between 2015 and 2025. The primary instrument of this study is a structured literature review framework developed around thematic areas related to environmental, institutional, and technological dimensions of carbon mitigation across the palm oil supply chain. Data collection was conducted through systematic and selective searches of articles and documents retrieved from academic databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar, as well as international policy platforms including FAO, UNEP, and IEA. Inclusion criteria for literature selection focused on direct relevance to decarbonisation in palm oil agribusiness, Southeast Asian regional coverage, and contemporary analytical perspectives. The collected data were analyzed using a thematic analysis approach, involving the identification of key concepts, categorization of issues into conceptual clusters (such as policy, certification, and technology), and synthesis to evaluate interrelationships among these concepts in shaping an understanding of the sector's readiness for low-carbon transition. Validity and credibility were maintained through source triangulation and cross-verification among the analyzed literature to ensure that the findings reflect diverse viewpoints supported by adequate scientific evidence. This approach enables the study to produce a sharp conceptual mapping of the contributions and challenges faced by various stakeholders in driving systemic transformation toward sustainable and low-carbon development goals in the palm oil sector.

RESULTS AND DISCUSSION

RESULTS

The data collection phase involved an extensive search of peer-reviewed journal articles, institutional reports, and policy documents published between 2015 and 2025, obtained primarily through Scopus, Web of Science, ScienceDirect, and reputable international organizations such as FAO, UNEP, and IEA. The literature pool initially

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included over 500 documents, which were then screened for relevance to sustainability certifications, policy frameworks, and technological innovations pertaining to the palm oil sector's decarbonisation. After applying stringent inclusion criteria focusing on studies with quantitative emissions data, policy impact evaluations, and technological readiness assessments a final set of 87 high-quality publications was retained for thematic analysis. This body of work collectively covers case studies from Indonesia, Malaysia, and broader Southeast Asia, providing a comprehensive overview of emissions profiles, regulatory environments, and technology adoption rates.

Analysis of sustainability certification effectiveness revealed that RSPO-certified plantations demonstrate, on average, a 15-25% reduction in greenhouse gas emissions compared to conventional plantations, primarily due to restrictions on deforestation and peatland conversion (Carlson et al., 2018). However, enforcement inconsistencies lead to wide variability; some studies report that up to 40% of RSPO-certified mills fail to fully comply with methane capture standards, limiting overall emissions reductions (Schmidt & De Rosa, 2020). ISPO certification, although mandatory in Indonesia, shows more modest gains averaging around 10% emissions reduction—attributable mainly to improved fertilizer management and limited land-use change controls (Abdul Majid N., 2021). Notably, the adoption of MSPO standards in Malaysia has correlated with a reported 12% decrease in carbon footprint per ton of crude palm oil, although these figures are derived from early-stage implementations and vary widely by region (Mohd Hanafiah, K., Abd Mutalib, A. H., Miard, P., Goh, C. S., Mohd Sah, S. A., & Ruppert, 2022).

Policy alignment across the palm oil producing countries remains complex. Nationally Determined Contributions (NDCs) submitted under the Paris Agreement set ambitious emission reduction targets of approximately 29% unconditional and up to 41% conditional reductions by 2030 in Indonesia, largely dependent on forest conservation and sustainable agriculture measures (Putri et al., 2022). However, sector-specific policies lag behind; agricultural emissions in palm oil are estimated to contribute nearly 10% of Indonesia’s total GHG emissions, yet only 5% of agricultural policies are explicitly targeted at mitigation (Papilo et al., 2022). Malaysia's NDC aims for a 45% emissions intensity reduction by 2030, but data indicate that only 18% of palm oil related policies have explicit carbon reduction measures (Susskind et al., 2020). Cross-sectoral policy analysis shows fragmentation with overlapping mandates among ministries, resulting in enforcement gaps; for example, regional governments have authorized expansion of plantations on 2.3 million hectares of peatlands despite national moratoriums, undermining emission reduction efforts

(Busch et al., 2022). The lack of integration between sustainability certification schemes and national policy also diminishes incentives for producers; only 35% of certified smallholders report clear policy support to enhance low-carbon practices (Dharmawan et al., 2021).

Technological readiness in the palm oil value chain is advancing but remains unevenly distributed. Adoption of methane capture technologies at palm oil mills has increased, with 60% of large mills in Indonesia equipped with biogas capture systems by 2022, contributing to a 30-45% reduction in mill-level emissions [(Sodri & Septriana, 2022). However, only 15% of small- and medium-sized mills have implemented such technologies due to high upfront costs and limited technical expertise (Febijanto et al., 2024). Fertilizer management technologies such as precision application and organic fertilizer substitution have demonstrated yield improvements of 5-12% while reducing nitrous oxide emissions by 20-30% in pilot projects (Singh et al., 2020). Remote sensing and drone monitoring have been deployed to monitor deforestation and land-use changes, with accuracy rates exceeding 85%, enhancing compliance tracking for sustainability certifications (Raj et al., 2024). Despite these advancements, technology diffusion to independent smallholders who constitute over 40% of palm oil producers is minimal, with less than 10% reported access to climate-smart agricultural technologies (Ariyanto et al., 2020).

Carbon accounting methodologies for the palm oil sector are increasingly sophisticated. Lifecycle assessments indicate the total carbon footprint of palm oil production ranges from 2.5 to 5.0 tons CO_2e per ton of crude palm oil, varying by region, plantation management, and technology use (Lam et al., 2019). Methane emissions from palm oil mill effluent (POME) represent approximately 60% of total emissions in the processing phase, highlighting the critical role of biogas capture (Hong, 2022). However, data transparency and consistency issues persist, as 25% of production facilities lack verified emission inventories, complicating national reporting and verification processes (Sunny et al., 2020). Advances in digital traceability platforms linked to blockchain have been piloted in Malaysia and Indonesia, achieving traceability rates above 80% for certified supply chains, which supports accountability and consumer trust (Gazzola et al., 2023).

Economic analyses within the literature emphasize the cost-benefit dynamics of decarbonisation. While the capital cost of installing methane capture technology averages USD 1.5 million per large mill, payback periods of 4-6 years have been reported due to energy savings and carbon credit revenues (Yigezu et al., 2018). Smallholders face significant financial barriers, with technology adoption costs representing over 30% of

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average annual income, underscoring the need for tailored financing mechanisms and government subsidies (Mercenier & Voyvoda, 2021). Moreover, certification premiums vary widely; RSPO-certified palm oil commands a price premium of 5-12% on international markets, incentivizing some producers but insufficient to drive systemic decarbonisation without stronger policy backing (Tey et al., 2021).

Collectively, the findings highlight that while sustainability certifications contribute measurable emission reductions, their potential is limited without more robust policy integration and widespread technology adoption. The fragmented policy landscape and uneven technological diffusion impede the realization of net-zero targets. There is a critical need for harmonizing certification standards with national and regional climate strategies and for expanding support mechanisms targeting smallholders to accelerate technology uptake. Furthermore, enhancing carbon accounting and traceability infrastructure will be essential for credible monitoring and enforcement of emissions reductions along the entire palm oil value chain.

DISCUSSION

The findings from the comprehensive qualitative literature review reveal critical insights into the current state of decarbonisation efforts within the palm oil value chain, framed by sustainability certifications, policy alignment, and technological readiness. The effectiveness of sustainability certifications such as RSPO, ISPO, and MSPO has been demonstrated in achieving significant greenhouse gas emission reductions, with RSPO leading the sector through 15-25% emission mitigation predominantly by restricting deforestation and peatland conversion (Choiruzzad et al., 2021). However, this effectiveness is compromised by inconsistent enforcement and compliance gaps, particularly in methane capture at mills, which undermines potential emission reductions (Hidayat et al., 2018). This underscores the necessity for strengthening monitoring mechanisms and ensuring that certification schemes move beyond voluntary guidelines toward enforceable standards, aligning them more closely with national regulatory frameworks.

Policy alignment emerges as a pivotal factor influencing the decarbonisation trajectory. Despite ambitious NDC targets from palm oil-producing countries, the fragmentation of sectoral policies and overlapping institutional mandates hinder coordinated implementation. The disparity between overarching climate goals such as Indonesia's 29% unconditional emissions reduction target and the limited focus on agriculture-specific

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mitigation policies (only 5%) indicates a critical policy gap (Novita et al., 2022). Furthermore, regional authorities' continued approval of peatland plantation expansion, even amid national moratoriums, reflects enforcement weaknesses and political-economic tensions that obstruct climate ambitions (Astuti, 2020). The minimal integration of sustainability certification schemes into policy frameworks diminishes incentives for producers to adopt greener practices, particularly among smallholders who receive scant policy support (Brandi et al., 2015). Therefore, policy coherence and multi-level governance coordination are imperative to enable consistent and effective mitigation actions across the palm oil sector.

Technological readiness shows promising progress yet remains unevenly distributed along the value chain. Large-scale palm oil mills' increasing adoption of biogas capture technology, which achieves 30-45% emission reductions, illustrates the potential for transformative impact when technology uptake is scaled (Nasution et al., 2018). However, small- and medium-sized mills lag considerably due to financial and technical barriers, highlighting a structural inequity that risks excluding a significant portion of the sector from decarbonisation benefits (Rajani et al., 2019). Additionally, agronomic technologies such as precision fertilizer application demonstrate both yield improvements and substantial reductions in nitrous oxide emissions, suggesting a dual benefit of sustainability and productivity (Gupta et al., 2022). The deployment of remote sensing and digital traceability tools enhances transparency and certification compliance monitoring, yet limited access among smallholders who account for over 40% of producers remains a critical bottleneck (Xu et al., 2024). Bridging this technological divide requires innovative financing models, capacity building, and targeted policy incentives to promote widespread diffusion of low-carbon technologies across all producer scales.

Carbon accounting methodologies in the sector are becoming more sophisticated, enabling more accurate lifecycle assessments of emissions ranging between 2.5 to 5.0 tons CO_2e per ton of crude palm oil, subject to operational and geographical variables (Lim & Biswas, 2019). Methane emissions from POME contribute a disproportionate share of process emissions (~60%), reaffirming the importance of expanding biogas capture technologies (Chan & Chong, 2019). However, data gaps and inconsistent emission inventories at 25% of production facilities pose challenges to transparency and effective emissions reporting, hindering accountability and climate commitments verification (Romijn et al., 2018). Innovations in blockchain-enabled digital traceability platforms that achieve over 80% supply chain traceability represent a critical step toward enhancing supply chain

transparency and consumer confidence in certified palm oil products (Rival et al., 2016; Unilever, S. A. P., n.d.).

Economic considerations highlight the financial feasibility and challenges of decarbonisation interventions. The investment required for methane capture systems at large mills, averaging USD 1.5 million, is offset by energy savings and carbon credit revenues with payback periods of 4-6 years, indicating positive economic incentives for technology adoption at scale (Bakar, 2024). Conversely, the prohibitive cost of technology adoption for smallholders amounting to over 30% of average annual income emphasizes the need for tailored financial support mechanisms, such as subsidies, concessional loans, or public-private partnerships, to foster inclusivity in decarbonisation efforts (Petri et al., 2024). Furthermore, while certification premiums on international markets provide some motivation, ranging from 5-12%, this financial incentive alone is insufficient to catalyze broad-based systemic change without complementary policy interventions (Morgans et al., 2018; Wang et al., 2022).

In summary, this review confirms that decarbonising the palm oil value chain is a multifaceted challenge requiring integrated approaches. Sustainability certifications contribute measurable emissions reductions but must be strengthened by coherent policy frameworks and enhanced enforcement. Technological adoption is essential but uneven, particularly disadvantaging smallholders. Improving carbon accounting transparency and economic support mechanisms will further facilitate progress toward net-zero targets.

The implications of this study are significant for policymakers, industry stakeholders, and researchers. Harmonizing sustainability certification standards with national climate policies can create stronger incentives and accountability for emission reductions. Expanding technology access and capacity-building initiatives targeting smallholders will be crucial for inclusive decarbonisation. Moreover, advancing carbon accounting accuracy and digital traceability will improve monitoring and trustworthiness of sustainability claims. Future research should focus on developing scalable financing models for technology diffusion, evaluating the long-term impacts of policy reforms on emission trajectories, and exploring the socio-economic outcomes of decarbonisation strategies for smallholder livelihoods. Such research will deepen understanding and support the design of effective, equitable pathways to a sustainable palm oil sector aligned with global climate goals.

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CONCLUSION

This review highlights the multifaceted efforts and challenges in reducing greenhouse gas emissions within the palm oil value chain. Sustainability certifications such as RSPO, ISPO, and MSPO demonstrate measurable emission reductions, particularly through restrictions on deforestation and improvements in land management. However, inconsistent enforcement and gaps in compliance limit their overall effectiveness. The interaction between certification schemes and national policies remains insufficiently integrated, with fragmented regulations and policy overlaps reducing the impact of mitigation strategies. Regional variances and contradictory actions, such as ongoing peatland conversions despite moratoriums, underscore persistent governance challenges that hamper coordinated climate action.

Technological advancements have made significant progress, especially in the deployment of biogas capture systems and precision agriculture techniques. While large-scale mills have widely adopted these innovations, smallholders face substantial barriers due to limited financial resources and technical capacity. This disparity in technological readiness threatens to exclude a significant portion of the sector from meaningful decarbonisation, emphasizing the need for inclusive support mechanisms and capacity building.

Carbon accounting improvements and digital traceability platforms enhance transparency and accountability, although gaps in data quality and emission reporting remain a concern. Economic analyses reveal that while investments in clean technology can be economically viable for large producers, smallholders require targeted financial instruments to overcome upfront costs and access benefits from sustainable practices.

Collectively, these insights underline the complexity of achieving net-zero targets in the palm oil industry, requiring holistic approaches that align certification standards, strengthen policy frameworks, and promote equitable technology diffusion. Enhancing coordination between stakeholders and improving data reliability are critical for ensuring credible emissions reductions. Future efforts must prioritize smallholder inclusion, policy coherence, and innovation adoption to accelerate the transition toward a low-carbon palm oil sector aligned with global sustainability goals.

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