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Harnessing palm oil for climate change mitigation: pathways to net zero emissions

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Abstract

This study investigates the potential of the palm oil industry to contribute to climate change mitigation and achieve net-zero emissions by evaluating current technologies, policy frameworks, and sustainable practices. A qualitative literature review was conducted, synthesising findings from over 80 peer-reviewed articles and policy reports published in the last two decades. Data were systematically collected from databases such as Scopus, ScienceDirect, and Web of Science, and analysed using thematic content analysis to identify key themes in innovation, policy implementation, and environmental and social impacts. Technological interventions, including methane capture from palm oil mill effluent and precision agriculture, have reduced emissions by 30% to 90%. Policy frameworks like RSPO and ISPO show promise but require more inclusive enforcement and broader adoption. The sector's mitigation potential is significant if supported by cohesive strategies. Palm oil plays a pivotal role in climate change mitigation when managed sustainably and supported by robust policies. While technological and policy advances have reduced emissions, challenges remain in scaling these solutions for smallholders. Stakeholders should focus on scaling sustainable technologies, enhancing smallholder inclusion, and strengthening enforcement of sustainability standards. Empowering smallholders is critical for aligning the sector with global net-zero ambitions.

Keywords: Climate change mitigation, Emission reduction, ISPO, Net zero pathways, Palm oil, RSPO, Sustainable agriculture.

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Contents

Contribution of this paper to the literature

This paper advances the literature by providing a comprehensive, integrative review of technological, policy, and socio-environmental pathways for leveraging palm oil in climate change mitigation, critically highlighting both the sector's emission reduction potential and the barriers to achieving net-zero goals, especially for smallholders and sensitive ecosystems.

1. Introduction

Global warming and environmental shifts, recognised as one of the most pressing issues of the 21st century, have a profound and lasting impact on ecosystems, global economic stability, and social justice [1]. Scientific consensus confirms that human-driven greenhouse gas (GHG) emissions, primarily stemming from the burning of fossil fuels and alterations in land use, are the primary contributors, and agricultural expansion is the primary driver of rising global temperatures [2]. In response, the global community, through accords such as the Paris Agreement and subsequent national commitments, has mobilised efforts to achieve net-zero emissions, typically targeting the mid-21st century [3]. However, while decarbonization strategies have primarily centered around energy and industrial systems, land-based solutions are increasingly recognised as vital, particularly in developing countries with vast natural resource endowments [4].

Together, agriculture, forestry, and other land-related activities (AFOLU) are responsible for nearly a quarter of global greenhouse gas emissions [5]. The expansion of oil palm plantations in this industry symbolises the ongoing tension between economic growth and potential ecological degradation [6]. Palm oil, being the highest-yielding oilseed crop per hectare, holds a pivotal position in global food production systems, cosmetics, and increasingly, bioenergy markets [7]. Yet, its cultivation has also been widely unfairly criticised for contributing to deforestation, peatland destruction, biodiversity decline, and the displacement of indigenous and rural populations, especially in Southeast Asia [8]. Therefore, the palm oil sector has faced both unfair criticism and reform initiatives, often simultaneously [9].

As the leading global producer and exporter of palm oil, Indonesia plays a crucial role in the sector and occupies a pivotal position within this complex matrix [10]. The industry is economically significant, contributing over 3.5% to Indonesia's GDP and supporting the livelihoods of millions of smallholders [11]. Nonetheless, emissions of greenhouse gases due to land use modifications, particularly the clearing of carbon-rich peatlands, have positioned Indonesia among the top global emitters during El Niño-induced fire seasons [12]. Recognising this, the Indonesian government has pledged to reduce emissions by 31.89% without international support and by 43.20% with international support by 2030, with the palm oil industry being crucial to achieving these goals [13].

In recent years, attention has shifted toward exploring the role of palm oil, not only as a source of emissions, but also as part of the solution to the climate crisis. Bioenergy derived from palm oil, if developed sustainably, has the potential to serve as a low-carbon fuel substitute [14]. Furthermore, capturing methane from palm oil mill wastewater (POME), carbon sequestration through agroforestry systems, and sustainable intensification techniques have been highlighted as viable mitigation strategies [15]. Organisational frameworks, such as the Roundtable on Sustainable Palm Oil (RSPO) and the Indonesian Sustainable Palm Oil (ISPO) certification programs, as well as jurisdictional approaches to sustainability governance, aim to institutionalise best practices across the value chain [16]. Despite these initiatives, the sector continues to face implementation barriers, including weak enforcement, policy incoherence, and divergent stakeholder interests [17].

Academic and policy debates have often been polarised, with some unfairly framing palm oil as inherently unsustainable. In contrast, others argue that, under the right regulatory and technological frameworks, it could make a meaningful contribution to climate mitigation and inclusive development [18]. However, a lack of integrative, critical synthesis remains, which bridges these discourses and assesses the whole landscape of potential mitigation pathways in the context of net-zero emissions [19]. Many existing reviews are either too narrow in scope or lack the conceptual depth required to inform transformative policymaking and cross-sectoral integration [20].

This article addresses this gap by conducting a qualitative literature review to examine the contribution of palm oil to mitigating climate change. It aims to synthesise key themes, contradictions, innovations, and policy frameworks found across the literature, with a particular focus on how the sector holds the potential to contribute towards meeting net-zero emissions goals. Through a critical and interpretive analysis of peer-reviewed and grey literature, the study aims to outline viable pathways for aligning palm oil production with environmental sustainability, social justice, and long-term climate objectives.

2. Literature Review

2.1. Palm Oil and Land-Based Emissions: The Global Dilemma

Palm oil has long been situated at the intersection of agricultural development and environmental degradation. While the crop is known for its high oil yield and economic efficiency, its cultivation has been extensively linked to land-use change, particularly accused of deforestation and peatland drainage, both of which are high-emission activities [21]. Several studies have highlighted the significant contribution of the rapid expansion of oil palm plantations, particularly in Indonesia and Malaysia, to carbon emissions over the last two decades [22]. This trajectory raises critical concerns about the sector's compatibility with global decarbonization goals [23].

2.2. Theoretical Linkages Between Agriculture and Climate Mitigation

The agricultural sector presents a complex landscape of both emission sources and potential sinks. From a theoretical perspective, sustainable agriculture aligns with the principles of ecological modernisation and climate justice, which advocate for technological innovation and equitable development [24]. The Intergovernmental Panel on Climate Change (IPCC) recognises agriculture, forestry, and other land-based activities (AFOLU) as essential components in strategies for mitigating climate change, especially when integrated with land restoration and bioenergy strategies [25]. Palm oil—given its dual role as a food and energy crop—has thus emerged as a focal point in the debate over land-based mitigation strategies [26].

2.3. Palm Oil in National and Global Climate Policy Frameworks

The involvement of palm oil in climate policy has been characterised by ambiguity. On the one hand, it is featured in national development plans and economic blueprints; on the other hand, it is often excluded or restricted in international biofuel certification regimes due to unfair concerns over sustainability [27]. Indonesia, for instance, has integrated the palm oil sector into its Nationally Determined Contribution (NDC) framework and its Low Carbon Development Strategy [27]. However, tensions remain between economic imperatives and environmental responsibilities, especially regarding enforcement, land tenure, and transparency in carbon accounting [28].

2.4. Sustainability Certification and Governance Challenges

In response to the sustainability challenges, several certification schemes have been developed, with the Roundtable on Sustainable Palm Oil (RSPO) and Indonesian Sustainable Palm Oil (ISPO) working to define and enforce responsible production standards [29]. However, these initiatives have been criticised for their voluntary nature, limited inclusion of smallholders, and inconsistent auditing practices [30]. Furthermore, studies reveal that certification does not always guarantee reduced deforestation or lower emissions, underscoring the need for integrated governance that extends beyond market-based instruments [31].

2.5. Technological Innovation and Emission Reduction Potential

Recent advancements in palm oil processing and plantation management have created new opportunities for reducing emissions. This includes the collection of methane from palm oil mill wastewater (POME), precision agriculture, zero-burning policies, and the conversion of degraded land rather than primary forests [32]. Some research suggests that the rigorous adoption of best practices could make palm oil-based biodiesel a net positive contributor to national carbon budgets [33]. However, scalability remains limited due to cost barriers, lack of incentives, and institutional fragmentation [34].

2.6. Socio-Ecological Trade-offs and Equity Considerations

Mitigation efforts in the palm oil sector must also consider the socio-ecological trade-offs, particularly for indigenous peoples, smallholders, and local communities [35]. Land acquisition practices, overlapping spatial planning, and unequal distribution of benefits continue to exacerbate vulnerability in rural areas [36]. This calls for a justice-oriented approach to mitigation, one that foregrounds inclusive participation and social safeguards in environmental policymaking [37].

2.7. Research Gaps and Emerging Discourses

While the literature on palm oil and climate mitigation is growing, several gaps remain. There is limited research on the long-term carbon balance of oil palm landscapes under different management regimes. Moreover, the integration of palm oil into circular economy models, carbon pricing mechanisms, and regional emissions trading schemes is still underexplored [38]. Emerging discourses now emphasise systems thinking, multi-scalar governance, and adaptive strategies that align palm oil development with planetary boundaries [39].

3. Method

This study utilises a qualitative research method, employing a critical and analytical literature review. The study aims to explore the role of palm oil in climate change mitigation by reviewing and synthesising findings from various relevant literature sources. This qualitative research focuses on the collection, analysis, and interpretation of published academic journal articles, academic papers, policy reports, and other related documents. The research instrument used is a thematic analysis of the selected sources, which were chosen based on relevance, validity, and academic quality criteria. Data collection was conducted through literature searches using academic databases, including Google Scholar, Scopus, and Mendeley, which yielded over 80 relevant articles and reports on the impact of palm oil on carbon emissions and its potential to contribute to climate change mitigation. The collected data was then analysed through qualitative descriptive analysis to identify key themes, trends, and deficiencies within the existing literature, with a focus on technological innovations, policies, and sustainable practices that can contribute to net-zero emissions goals. The data analysis process involved mapping the relationships between findings, grouping main topics, and evaluating the consistency and methodological quality of each study reviewed. By employing this approach, the study aims to provide a deeper understanding of the challenges and opportunities the palm oil industry faces in contributing to global climate change mitigation.

4. Results

The following section summarises the outcomes of the qualitative literature assessment, focusing on the role of palm oil in climate change mitigation and its potential pathways to achieving net-zero emissions. The data for this review were collected through comprehensive searches of over 80 peer-reviewed journal articles, academic papers, policy reports, and other relevant sources, accessed from databases such as Scopus, Google Scholar, and Mendeley. These sources were systematically analysed to provide insights into technological innovations, policy frameworks, environmental impacts, as well as the social and economic factors surrounding the palm oil industry.

4.1. Technological Innovations and Emission Reduction Potential

Technological advancements have significantly reduced the environmental impact of palm oil farming and production in terms of carbon emissions. One of the most impactful innovations is the capture of methane from palm oil mill effluent (POME), a potent greenhouse gas. The implementation of methane capture systems has been shown to reduce approximately 80-90% of methane emissions from palm oil mills, contributing to a substantial decrease in overall greenhouse gas emissions from palm oil production. This technology has been implemented at scale in Malaysia and Indonesia, resulting in a reduction of up to 60% in the carbon footprint of palm oil mills [40]. Furthermore, data from various case studies indicate that methane capture has not only reduced emissions but also provided additional revenue streams for mill operators through the sale of biogas [41].

Another notable technological advancement is the adoption of zero-burning policies for land preparation, which significantly mitigates emissions from forest and peatland fires prevalent in regions where palm oil expansion is occurring. Research indicates that enforcing zero-burning policies can reduce carbon emissions by up to 75% compared to conventional methods that involve fire [42]. Precision agriculture, which incorporates the use of drones, remote sensing technologies, and automated irrigation systems, has further optimised palm oil yields while minimising impacts on sensitive ecosystems. These innovations have increased palm oil yields by 20-30% without necessitating additional land clearance [43].

Despite the progress, these technologies face substantial barriers to adoption, especially among smallholder farmers, who contribute to 40-45% of palm oil production in both Indonesia and Malaysia. The high upfront costs of adopting methane capture systems and precision agriculture, coupled with limited access to financial support and training, remain significant challenges [44].

4.2. Policy and Governance Frameworks

The policy landscape surrounding palm oil production is multifaceted, encompassing both national regulations and voluntary certification schemes. Founded in 2004, the Roundtable on Sustainable Palm Oil (RSPO) remains the most prominent certification body for sustainable palm oil, promoting environmental best practices. However, RSPO-certified palm oil still accounts for only 19% of global production, highlighting significant barriers to its broader adoption [45]. High certification costs, particularly for smallholders, and weak enforcement mechanisms in regions with inadequate governance structures exacerbate these challenges.

National initiatives, such as Indonesia's ISPO certification and Malaysia's MPOCC, have been established to promote sustainability in the palm oil sector. However, implementation remains uneven, with approximately 15-20% of palm oil plantations in Indonesia operating outside of any sustainability framework [46]. Furthermore, inconsistent enforcement of zero-deforestation policies and land tenure laws continues to undermine efforts to reduce deforestation, particularly in sensitive peatlands and primary forests [47].

Indonesia's Low Carbon Development Strategy (LCDS), launched in 2019, incorporates palm oil as a critical component of its climate strategy, aiming for a 29% reduction in sector emissions by 2030 compared to a business-as-usual scenario [48]. However, challenges persist in coordination between local, regional, and national governments, hindering effective policy implementation and achieving climate goals [49].

4.3. Environmental and Social Trade-Offs

The growth of palm oil plantations has led to accusations of widespread deforestation, with an estimated 10 million hectares of forest converted into oil palm plantations between 1990 and 2020 [50]. Such deforestation leads to substantial carbon emissions due to land-use change and results in severe potential biodiversity loss. For instance, accusations of habitat destruction related to palm oil expansion have been a key factor in the 70% decline in orangutan populations in Sumatra [51]. Moreover, the drainage of peatlands for palm oil cultivation has resulted in massive carbon emissions, with studies finding that peatland conversion can release up to 10 times more carbon than cultivation on mineral soils [52].

On the social front, smallholder farmers, who produce a significant portion of palm oil, often face issues such as insecure land tenure, limited access to modern agricultural technologies, and poor compensation. An estimated 4 million people depend on palm oil for their livelihoods, yet some smallholders remain trapped in poverty and experience low productivity [53]. Policies aimed at improving smallholder livelihoods, such as providing access to training, financial support, and market access, are essential for addressing these social challenges while advancing climate mitigation goals [54].

4.4. Gaps and Future Research Directions

Despite considerable progress in understanding the contribution of palm oil cultivation and usage to efforts in addressing climate change impacts, several research gaps persist. A significant gap exists in the sustained equilibrium of carbon stocks within oil palm plantation ecosystems over extended periods, particularly among those implementing sustainable intensification practices. Life Cycle Assessment (LCA) studies indicate that land-use changes and the management practices mainly employed influence the carbon footprint of palm oil. However, comprehensive research on the carbon sequestration potential of palm oil plantations, particularly those employing sustainable practices, remains scarce [55].

Moreover, the effectiveness of sustainability certification schemes such as RSPO remains inconsistent, particularly for smallholders, due to challenges in accessibility and enforcement [56, 57]. Future research should investigate strategies to enhance the scalability and enforcement of certification standards, thereby ensuring broader compliance. Lastly, there is a pressing need for studies investigating the economic feasibility of emission-reduction technologies, such as methane capture, for smallholder farmers, to bridge the structural and capacity gaps between commercial plantations and small-scale growers [58, 59].

This review reveals that palm oil holds considerable promise as a contributor to strategies aimed at mitigating climate change. Technological innovations, such as methane capture and precision agriculture, present promising solutions to reduce emissions; however, financial and infrastructural challenges hinder their widespread adoption. Policy frameworks such as RSPO and ISPO provide a foundation for sustainable practices but require improved enforcement and broader adoption. The ongoing deforestation driven by palm oil expansion, along with its associated environmental impacts, must be addressed through stricter governance and stronger regulatory frameworks. Ultimately, empowering smallholder farmers is crucial for achieving sustainable palm oil production and supporting broader climate objectives. Enhancing the reliability of carbon balance modelling should be a central objective in subsequent research, thereby improving the effectiveness of sustainability certifications and exploring innovative pathways to scale emission-reducing technologies in smallholder contexts.

5. Discussion

The evidence presented underscores the potential of palm oil as a key player in climate mitigation initiatives, particularly through the adoption of innovative technologies and effective policy frameworks. The literature reviewed provides compelling evidence of the potential to utilise palm oil as an environmentally sustainable commodity, although challenges related to its potential environmental and social impacts remain substantial. The findings from the collected data highlight the effectiveness of current technologies and policies in reducing emissions from palm oil production, while also emphasising the need for continued efforts to address the underlying barriers to scaling these practices, particularly for smallholders [60].

Advancements in technology are recognised as essential for minimising the ecological impact associated with palm oil cultivation. Implementing methane recovery technologies in palm oil processing facilities has demonstrated potential in substantially reducing greenhouse gas emissions. Through the extraction of methane from palm oil mill effluent (POME), up to 90% of methane emissions—one of the most potent greenhouse gases—can be mitigated [61]. Large-scale implementations in Malaysia and Indonesia have demonstrated emission reductions of up to 60%, confirming the viability of such interventions [62]. Despite their significant role in global palm oil production, smallholder farmers frequently face challenges in accessing the financial means and technical expertise required to adopt these solutions, which calls for the development of inclusive financing mechanisms and training programs [63].

A further advancement lies in the implementation of zero-burning policies during land clearing, which can reduce carbon emissions by up to 75% compared to traditional fire-based methods [64]. Precision agriculture technologies, including the use of drones and remote sensing, have contributed to yield increases of 20–30% without expanding plantation areas, thereby preserving forest ecosystems and minimising land-use change [65]. Yet, these technologies remain costly and inaccessible primarily to smallholders, reinforcing the technological divide within the sector [66].

Regulatory frameworks have played a crucial role in promoting sustainability within the palm oil sector. The Roundtable on Sustainable Palm Oil (RSPO) has established globally recognised standards; however, only 19% of global palm oil production is certified, largely due to high compliance costs and enforcement gaps [67]. These limitations are particularly pronounced in regions dominated by smallholder production, where certification is both financially and administratively burdensome [68]. Enhancing accessibility to certification, streamlining compliance processes, and strengthening enforcement mechanisms are key to expanding sustainable practices [69].

National policy efforts, such as Indonesia's ISPO and Malaysia's MPOCC certification schemes, have sought to institutionalise sustainability. Despite progress, these initiatives often suffer from inconsistent implementation and limited coordination among stakeholders at different governance levels [70]. In some cases, weak regulatory oversight potentially may have allowed illegal land conversion for palm oil plantations to continue, undermining broader environmental objectives [71]. Strengthening institutional governance and harmonising regulatory frameworks across jurisdictions are essential for achieving long-term climate benefits [72].

Accusations of environmental consequences, including widespread deforestation and biodiversity loss, remain pressing concerns. It has been accused that over 10 million hectares of tropical forest might have been cleared for palm oil cultivation, contributing to the decline of species such as the orangutan, whose populations have decreased by up to 70% in affected areas [73]. Furthermore, the expansion of plantations into peatland areas has released carbon emissions up to ten times higher than those associated with mineral soil cultivation, due to the high carbon content stored in peat [74]. Halting further encroachment into carbon-rich ecosystems and enforcing land-use zoning regulations are critical to reversing these impacts [75].

Social factors are also crucial in shaping the long-term sustainability of the industry. Smallholder farmers face persistent challenges, including insecure land tenure, limited access to sustainable farming inputs, and weak integration into formal supply chains [76]. Although they account for an estimated 40–45% of global palm oil production, some smallholders may remain trapped in cycles of low productivity and poverty. Tailored policy interventions that provide financial support, technical training, and market access are needed to empower smallholders as agents of sustainable transformation [77].

Despite valuable insights from the existing literature, several critical knowledge gaps remain. Notably, the long-term carbon balance and sequestration potential of oil palm plantations remain largely unexplored. While technologies such as methane capture and zero-burning reduce emissions, holistic assessments of life-cycle emissions and carbon sinks remain scarce [78]. Similarly, the economic feasibility of implementing advanced technologies among smallholders warrants further study. Most small-scale producers lack the capital and support systems necessary to transition to more sustainable practices, underscoring the need for cost-effective and scalable solutions tailored to their specific context [79, 80].

The implications of this research suggest that, despite its promise, palm oil has the potential to be an active contributor to mitigating climate change; the industry must undergo a structural transformation to align with global net-zero goals. Technological innovations such as methane capture and precision agriculture, combined with more robust policy enforcement and inclusive governance, offer viable paths to reducing the carbon intensity of palm oil production. These interventions must be integrated with social policies that empower smallholders and protect biodiversity and carbon-dense ecosystems. Future research should focus on refining carbon accounting models, scaling sustainable technologies for smallholders, and developing more effective and accessible certification schemes. Addressing these multidimensional challenges can position the palm oil sector as a key player in the transition toward a future with net-zero emissions.

6. Conclusion

The analysis of existing literature reveals that palm oil has considerable potential to support climate change mitigation when managed through sustainable practices and supported by robust policy frameworks. Technological innovations, including methane recovery technologies and land preparation methods that avoid burning, have demonstrated measurable impacts in reducing greenhouse gas emissions. These practices, particularly when integrated with precision agriculture tools, offer a practical pathway to improve productivity while minimising environmental degradation.

Sustainability certifications, along with national policy measures, have played a crucial role in guiding the palm oil industry toward adopting more environmentally responsible practices. However, limited adoption—especially among smallholder farmers—continues to hinder widespread implementation. Challenges such as substantial costs, a lack of technical expertise, and fragmented policy enforcement reduce the overall effectiveness of these interventions. Enhancing access to finance, technology, and market mechanisms is therefore critical to ensuring broader participation and greater impact.

Environmental risks remain significant, mainly deforestation, biodiversity loss, and peatland degradation. The conversion of carbon-rich ecosystems continues to release vast quantities of emissions, thereby undermining the gains made in mitigation. A shift toward protecting high-conservation-value areas and avoiding further expansion into sensitive zones is essential to preserving environmental integrity.

Social dimensions, particularly the empowerment of smallholder farmers, are central to the success of mitigation strategies in the palm oil sector. Providing secure land tenure, access to sustainable resources, and training can enhance productivity and improve livelihoods, while ensuring that these practices align with broader sustainability objectives.

The potential of palm oil as a climate change mitigation solution hinges on collaborative efforts among all relevant stakeholders, including governments, industry actors, and civil society. Strengthening governance, enhancing policy enforcement, and incentivising the adoption of innovation and sustainability at all levels will be key to unlocking the sector's full potential. Continued research into lifecycle emissions, socio-economic integration, and technology scalability will further guide this transition toward a net-zero emissions future.

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