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Environmental Impacts of Palm Oil Cultivation: A Systematic Review of Carbon Emissions, Biodiversity Loss, and Land Use Change

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ABSTRACT
The rapid expansion of palm oil cultivation has generated major environmental concerns, especially in tropical regions facing deforestation, habitat loss, and rising greenhouse gas emissions. This study conducts a qualitative Systematic Literature Review (SLR) using the Scopus database to synthesize recent findings on the environmental effects of palm oil, focusing on carbon emissions, biodiversity loss, and land use change. From 1,985 publications, a screening process (2022–2025, English, Open Access) identified 12 eligible studies. Thematic synthesis revealed three main issues: (1) high carbon emissions from peatland drainage; (2) biodiversity decline due to deforestation; and (3) land degradation from extensive conversion. Although sustainability certifications and zero-deforestation policies exist, implementation remains inconsistent. Further research integrating remote sensing and life cycle assessment (LCA) is recommended to strengthen regional sustainability frameworks.

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INTRODUCTION

Environmental degradation is a critical global challenge, as industrial growth, agriculture, and population pressures drive emissions, deforestation, and biodiversity loss, pushing ecosystems toward dangerous tipping points. Agricultural expansion, especially in tropical regions, is a major contributor to carbon emissions, habitat destruction, and land use change. The conversion of forests and peatlands into farmland releases significant carbon stocks, responsible for about 11% of global CO_2 emissions, while also accelerating species extinction and ecosystem degradation. Consequently, land use change has emerged as a central driver linking climate change, biodiversity decline, and environmental instability.

Earlier research has extensively examined the nexus between carbon emissions, biodiversity loss, and land use change, each revealing how these phenomena reinforce one another within complex ecological systems. For instance, (Liu et al., 2020) demonstrated that carbon emissions resulting from tropical deforestation are not merely a by-product of land clearing but also a catalyst for long-term soil carbon depletion and hydrological imbalance. Similarly, (Meijaard et al., 2020) emphasized that land use transitions, particularly from forests to monoculture plantations, lead to irreversible biodiversity degradation, where the reduction in habitat complexity lowers resilience against climate variability. Both studies converge on the conclusion that the environmental consequences of land use change extend far beyond local ecosystems, influencing global climate regulation and biodiversity integrity

While the global academic community has made substantial progress in mapping these relationships, research specifically addressing the environmental impacts of land use transitions remains critical. Two recent studies highlight the growing attention to this issue. (Mardiana & Hasibuan, 2023) and (Medvedkov, 2024) analyzed global patterns of environmental impact from agricultural intensification, concluding that cumulative emissions from land use change are underestimated in national inventories. Likewise, van der (Teng et al., 2020) revealed that indirect effects of land conversion such as peat oxidation and soil compaction contribute substantially to net carbon fluxes. Both investigations underline that environmental impacts are multidimensional, incorporating not only carbon dynamics but also the degradation of biotic and abiotic systems.

Two studies in particular underscore the urgency of this issue. (Abdullah et al., 2025) examined land use transitions in Indonesia and Malaysia, showing that oil palm expansion is the leading cause of peatland loss and a major contributor to regional carbon emissions. Similarly, (Estrada et al., 2020) and (Purnomo et al., 2019) reported that oil palm monocultures reduce forest biodiversity by up to 80% compared with primary forests, with significant implications for ecosystem resilience and carbon cycling.

Building upon the earlier research strands, five key empirical insights connect palm oil cultivation with broader environmental impacts. First, deforestation driven by plantation expansion results in immediate and long-term carbon emissions. Second, the loss of native vegetation leads to habitat fragmentation, diminishing biodiversity. Third, peatland drainage associated with palm oil production releases stored carbon and increases fire susceptibility. Fourth, land conversion modifies local climate regulation through altered evapotranspiration and albedo effects. Fifth, socio-economic pressures to expand production often override sustainability initiatives, perpetuating cycles of environmental degradation.

To address these multidimensional problems, scholars and policymakers have proposed various mitigation strategies grounded in ecological and socio-economic theories. Two theoretical frameworks are particularly relevant. The first is the Ecological Modernization Theory (EMT), which posits that environmental sustainability can be achieved through technological innovation, institutional reform, and market-based mechanisms without sacrificing economic growth. EMT suggests that cleaner production technologies, sustainability certification (such as RSPO or ISPO), and green policy integration could mitigate palm oil's environmental footprint. The second is the Planetary Boundaries Framework (Carr et al., 2023) and (Arachchige et al., 2019).

This study conducts a Systematic Literature Review of Scopus-indexed articles (2022–2025) to assess palm oil's impacts on carbon emissions, biodiversity loss, and land use change, ensuring transparency and rigor through published data analysis.

This study aims to (1) identify palm oil's main environmental impacts—carbon emissions, biodiversity loss, and land use change, and (2) assess mitigation strategies and frameworks to reduce these effects. From these objectives, two research questions (RQs) are formulated to guide the review and will be discussed in depth in the subsequent sections:

RQ1: *What are the key environmental consequences of palm oil cultivation in terms of carbon emissions, biodiversity loss, and land use change?*

RQ2: *What mitigation strategies and theoretical approaches have been proposed to address these environmental challenges in the context of sustainable palm oil production?*

These questions structure the analytical direction of this review, providing the foundation for a comprehensive synthesis that contributes both to scientific understanding and to evidence-based policymaking on sustainable agricultural practices.

LITERATURE REVIEW

Understanding palm oil's environmental impact requires reviewing studies on carbon emissions, biodiversity loss, and land use change, particularly in tropical regions where these factors jointly shape its ecological footprint.

1. Overview of Environmental Impacts in Agricultural Systems

The expansion of agricultural frontiers across tropical regions has profoundly reshaped global environmental dynamics, driving concerns over deforestation, carbon emissions, and biodiversity degradation. Agriculture, as a cornerstone of global food and commodity production, contributes nearly one-quarter of anthropogenic greenhouse gas (GHG) emissions worldwide, largely through land-use change, deforestation, and soil degradation (Hernawan et al., 2025). Tropical countries like Indonesia and Malaysia, major palm oil producers, face the challenge of balancing economic growth with rising ecological costs from deforestation, climate change, and carbon disruption.

These domains are not isolated phenomena; rather, they constitute a feedback system in which deforestation for agricultural expansion releases stored carbon, habitat conversion threatens endemic species, and the cumulative transformation of landscapes alters ecological equilibrium. As global demand for agricultural commodities particularly palm oil continues to rise, understanding these interdependencies becomes critical for sustainable land management and environmental policy formulation (Correa et al., 2020; Nurhidayah et al., 2025).

2. Carbon Emissions and Palm Oil Expansion

Carbon emissions represent one of the most critical environmental outcomes of palm oil cultivation. The establishment of plantations frequently involves clearing carbon-rich peatlands and tropical rainforests, which act as major carbon sinks. Once cleared, these landscapes release vast quantities of CO_2 and methane, exacerbating global warming. Empirical studies have shown that oil palm expansion in Southeast Asia contributes significantly to regional carbon budgets, accounting for up to 10% of total deforestation-related emissions (Tölle, 2020).

Recent evidence also highlights the persistence of emissions even after plantation establishment, as soil carbon oxidation and peat subsidence continue to release greenhouse gases over time (Taheripour et al., 2019). Furthermore, plantation management practices such as fertilizer use and biomass burning amplify emissions from nitrous oxide and methane.

Mitigation efforts like peatland rewetting, zero-deforestation pledges, and RSPO certification are key strategies to reduce emissions in the palm oil industry.

3. Biodiversity Loss Associated with Palm Oil Cultivation

Biodiversity loss is another major environmental concern linked to palm oil expansion. The replacement of primary forests with monoculture plantations drastically alters habitat structures, leading to species decline and ecosystem simplification. Studies in Borneo and Sumatra have shown that oil palm landscapes support only a fraction of the species found in native forests particularly among birds, mammals, and invertebrates (Zhao et al., 2023). The loss of canopy continuity and understorey diversity disrupts ecological interactions, threatening species that depend on specific microhabitats.

4. Land Use Change and Environmental Transformation

Land use change (LUC) represents the underlying driver that integrates carbon emissions and biodiversity loss. Palm oil expansion epitomizes a rapid form of LUC that transforms complex forest ecosystems into simplified agricultural systems. Over the past three decades, Southeast Asia has witnessed one of the world's most rapid LUC trajectories, driven primarily by global demand for edible oils and biofuels (Beringer et al., 2023).

Furthermore, indirect land use change (ILUC) in which non-forest lands are converted elsewhere to compensate for displaced agricultural activity magnifies the environmental footprint of palm oil. For instance, when smallholder farms are displaced by industrial plantations, they often clear new forest areas, perpetuating a cycle of deforestation and emission leakage.

Recent geospatial modeling efforts have advanced understanding of LUC trajectories, highlighting hotspots where palm oil expansion intersects with high conservation value areas. However, integrating these models into actionable governance frameworks remains a challenge.

5. Integrative Studies on Environmental Impacts

A growing body of research has sought to synthesize these interrelated phenomena under the umbrella of environmental impacts. Environmental impact assessments (EIA) serve as the formal mechanism through which potential ecological consequences are evaluated prior to project approval. Studies by (Gopal et al., 2023) and (Soam & Hillman, 2019) provide comprehensive reviews linking oil palm expansion to cumulative environmental impacts, including air pollution, water contamination, and soil degradation.

6. Palm Oil Cultivation: Economic Growth vs. Environmental Degradation

Palm oil cultivation has been lauded as an economic success story, contributing substantially to export revenues, rural employment, and poverty reduction in producing countries. However, this economic success has come at a high environmental cost. The trade-off between economic development and environmental degradation represents the central paradox of the palm oil industry.

Several studies, including those by (Mohd-Azlan et al., 2023) and (Anshah et al., 2025), highlight this duality by demonstrating that while palm oil drives local economic benefits, its ecological externalities far outweigh short-term gains if sustainability principles are neglected. The rapid pace of expansion, coupled with weak governance, has exacerbated environmental degradation in regions lacking effective land-use regulation.

7. Theoretical Framework and Conceptual Synthesis

Palm oil’s environmental impacts can be understood through Ecological Modernization Theory and the Environmental Kuznets Curve, which suggest sustainability can be achieved through innovation and stronger governance. In contrast, the EKC framework suggests that environmental degradation initially increases with economic growth but eventually declines as societies attain higher income levels and environmental awareness (Ayompe et al., 2025; Lyons-White et al., 2025).

METHODOLOGY

This study applies a Systematic Literature Review (SLR) following the PRISMA protocol to assess palm oil’s environmental impacts—carbon emissions, biodiversity loss, and land use change—using only Scopus-indexed journal articles for transparency, rigor, and reproducibility.

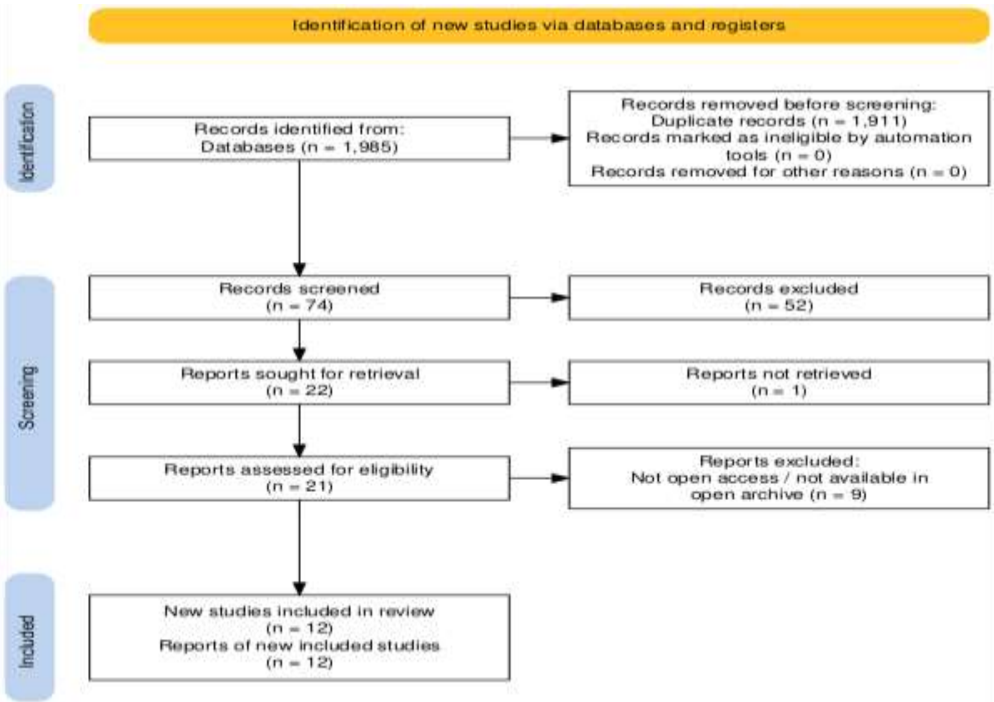

Figure 1. Systematic Literature Review Process Based on the PRISMA Protocol

Figure 1 illustrates the systematic procedure through which relevant studies were identified, screened, and selected for analysis. The process commenced with a broad keyword search using the term "palm oil environmental impact," which generated 1,985 publications. To enhance thematic precision, the search was refined using the Boolean string: *("palm oil" OR "oil palm" OR "palm oil cultivation" OR "oil palm plantation" OR "palm oil production" OR "palm oil expansion" OR "palm oil agriculture" OR "palm oil industry") AND ("environmental impact" OR "environmental effect" OR "environmental degradation" OR "environmental sustainability" OR "ecological impact" OR "sustainability assessment" OR "sustainable development") AND ("carbon emission" OR "greenhouse gas emission" OR "GHG emission" OR "carbon footprint" OR "climate change" OR "climate change impact" OR "global warming") AND ("biodiversity" OR "biodiversity loss" OR "species loss" OR "ecosystem degradation" OR "habitat loss" OR "ecosystem function") AND ("land use" OR "land use change" OR "land cover change" OR "deforestation" OR "forest conversion" OR "land transformation").*

This refinement excluded 1,911 records that fell outside the thematic scope of the study, leaving 74 potentially relevant publications. During the screening stage, a temporal filter was applied to capture recent research published between 2022 and 2025, which led to the removal of 52 articles published outside this period, resulting in 22 remaining records. In the eligibility stage, non-English language publications were excluded, eliminating one article and leaving 21 eligible studies. Finally, accessibility was imposed as the decisive inclusion criterion. Only open access and open archive publications were retained for analysis, leading to the exclusion of nine restricted-access studies. Consequently, 12 peer-reviewed journal articles satisfied all inclusion criteria and constituted the final dataset for in-depth synthesis and evaluation.

RESEARCH RESULT

The systematic review identified 12 peer-reviewed journal articles that met all inclusion criteria following the PRISMA screening process. These studies collectively explore the environmental implications of palm oil cultivation with emphasis on carbon emissions, biodiversity loss, and land use change. The final dataset, summarised in Table 1, represents research conducted across diverse geographical contexts, including Southeast Asia, Africa, and Latin America, reflecting the global scale of palm oil related environmental issues.

Table 1. Summary of Selected Studies on Environmental Impacts of Palm Oil Cultivation

No.	Author / Year	Title	Research Result
1.	J. B. Kauffman; M. F. Adame; W. C. Adinugroho; G. Anshari; I. Basuki; D. Donato; A. Gangga; D. Murdiyarso; R. P. Ritonga; M. Warren; N. Novita. (2025)	Total ecosystem carbon stocks of tropical peat forests and greenhouse gas emissions from their disturbance	A study of 125 tropical peat forests across four continents revealed peat depths ranging from 19 to 1414 cm, with total ecosystem carbon stocks (TECS) between 172 and 9379 Mg C ha^{-1} (average 2137 Mg C ha^{-1}). In 47 tidally influenced sites, TECS varied from 206 to 5591 Mg C ha^{-1}. Forests with peat deeper than 7 meters showed the highest carbon storage, averaging 4620 ± 395 Mg C ha^{-1}. Peat soils accounted for about 86% of total carbon, and peat depth was strongly correlated with soil carbon ($R^2 > 0.80$). Conversion of tropical peat forests, especially into oil palm plantations, generates major greenhouse gas emissions and severe ecological and social losses. The estimated social carbon cost is nine times higher than the economic return from palm oil, emphasizing the critical need to conserve and restore tropical peatlands for sustainable futures.
2.	Haniff Ahamat & Yuki Wong. (2025)	Pest Eradication and Environmental Sustainability Dilemma of Malaysia's Palm Oil	The study examines Malaysia's pest control regulations in the oil palm industry from an environmental perspective. It finds that while palm oil contributes significantly to the economy, its production causes deforestation, biodiversity loss, and greenhouse gas emissions. The use of chemical pesticides intensifies these issues, posing risks to ecosystems and public health. Analysis of the Environmental Quality Act 1974 and the Pesticides Act 1974 shows that, although environmental concerns are recognized, stronger coordination between environmental and agricultural policies is needed. The research, using doctrinal legal and limited empirical methods, concludes that improved governance and enforcement are essential to align pest management with sustainability goals and to ensure fair comparison of palm oil with other global oil crops.
3	Indra Purnama; Anisa Mutamima; Muhammad Aziz; Karna Wijaya; Iffana Dani Maulida; Junaidi Junaidi; Karmila Sari; Irwan Effendi; Isna Rahma Dini. (2025)	Environmental Impacts and the "Food vs. Fuel" Debate: A Critical Review of Palm Oil as Biodiesel	The review finds that while palm oil is an efficient and affordable biodiesel source, its large-scale cultivation causes serious environmental and social impacts. Major issues include greenhouse gas emissions, deforestation, biodiversity decline, and water and soil degradation. The study highlights how biodiesel expansion intensifies the "food versus fuel" conflict, especially in developing regions such as Indonesia and Malaysia. It emphasizes that peatland conversion

			significantly increases carbon emissions and ecological loss. The research also notes that sustainability certification schemes like RSPO and ISPO have limited effectiveness. Overall, the study concludes that balancing energy needs, food security, and environmental protection requires stronger policies, improved land management, and adoption of cleaner technologies.
4	Suzanne McGowan; Jack H. Lacey; Stefan Engels; John Boyle; Charlotte Briddon; Melanie J. Leng; Heather L. Moorhouse; Virginia Panizzo; Muhammad Shafiq. (2024)	Land use, hydroclimate and damming influence organic carbon sedimentation in a flood pulse wetland, Malaysia	Sediment analyses from Tasik Chini, Malaysia, show that land use changes since the 1940s especially deforestation, plantation expansion, and mining have greatly increased organic carbon accumulation. The median rate since 1945 was 85 g m^{-2} a^{-1}. Human activities and water regulation, including a 1995 weir installation, shifted carbon sources between soil-derived and in-lake production, revealing strong human influence on wetland carbon storage and ecosystem dynamics
5	J. W. Gotschall, G. S. Silva & J. M. Grant-Kels. (2025)	Balancing Patient Benefits and Environmental Impacts of Emollient Ingredients: An Ethical Argument	Ethical and environmental implications of palm oil based emollients; links between biodiversity loss, deforestation, and climate change within dermatological and pharmaceutical contexts.
6	Ceisy Nita Wuntu, Devilito Prasetyo Tatipang, Olga A. Rorintulus, Merlin M. Maukar & Muhammad Ilham Ali. (2024)	Ecological Criticism in the Pastoral Narrative Luka Perempuan Asap by Nafi'ah al-Ma'rab	Using ecocritical and pastoral narrative analysis, the study examines Nafi'ah al-Ma'rab's Luka Perempuan Asap to explore environmental issues in Indonesia's oil palm plantation context. The findings show that deforestation linked to palm oil cultivation leads to pollution, habitat destruction, species extinction, and climate deterioration. The novel reflects diverse human attitudes toward nature, emphasizing respect, harmony, and responsibility for environmental preservation. Overall, it conveys a moral message about the dangers of exploiting nature and the urgent need for ecological awareness and stewardship.
7	Muhammad Ali Ijaz Malik, Sadaf Zeeshan, Muhammad Khubaib, Adeel Ikram, Fayaz Hussain, Hayati Yassin & Atika Qazi. (2024)	A review of major trends, opportunities, and technical challenges in biodiesel production from waste sources	The review highlights waste-derived biodiesel as a sustainable alternative to conventional fuels, reducing environmental harm from palm oil based production. It finds that waste cooking oil and animal fats are the most practical and cost-effective feedstocks, while algae show strong potential but remain limited by high costs and technology gaps. Various conversion methods such as transesterification, pyrolysis, and enzymatic processing affect efficiency and scalability. Although biodiesel from waste reduces CO and HC emissions, it increases NOx and CO_2 levels, which can be mitigated through emission control technologies. The study concludes that harmonized policies and continued research are essential to enhance sustainability and economic viability in waste-based biodiesel production.

8	B. Okarda; H. Purnomo; L. Juniyanti; S.D. Kusumadewi; S. Nadhira. (2024)	Indonesian palm oil towards sustainability: a system dynamic approach	This study introduces a dynamic model called SIPOS (Simulation of Indonesian Palm Oil Sustainability) to examine the link between Indonesia's palm oil industry, the economy, and the environment. The simulation reveals that plantation expansion significantly contributes to deforestation, peatland degradation, and greenhouse gas emissions. However, sustainability interventions such as intensification and the NDPE (No Deforestation, No Peat, No Exploitation) policy can reduce environmental harm while maintaining national economic benefits. The study highlights that dynamic system modeling is an effective tool for designing and comparing sustainability scenarios in Indonesia's palm oil sector.
9	Sophie-Dorothe Lieke; Achim Spiller; Gesa Busch. (2023)	Can consumers understand that there is more to palm oil than deforestation?	The study investigates German consumers' perceptions of palm oil, focusing on their awareness of its environmental and social implications. Using an online survey with 1,220 respondents, the research analyzes how people associate palm oil with deforestation, habitat loss, and biodiversity decline, while overlooking its high yield compared to alternatives like soybean oil. Findings show that providing factual information can improve understanding of indirect land use change, but it does not significantly enhance perceptions of certified palm oil's sustainability. Overall, awareness alone is insufficient to shift public opinion from a simplistic "good versus bad" view toward a nuanced understanding of palm oil's complex sustainability challenges.
10	Alejandro Calderón-Balcázar; Carlos D. Cárdenas; Oswaldo Díaz-Vasco; Emilio Fandiño; Tatiana Márquez; Camila Pizano. (2023)	Biomass and Carbon Stocks of Four Vegetation Types in the Llanos Orientales of Colombia (Mapiripán, Meta)	This study compares biomass and carbon storage between natural forests and oil palm plantations in Colombia's Orinoquía region. Using forest inventory data and allometric models, it found that natural forests store higher aboveground biomass and carbon (542.45 Mg ha−1) than oil palm plantations (284.87 Mg ha−1). Among vegetation types, morichal peat swamp forests had the greatest carbon accumulation (402.76 Mg ha−1). The findings emphasize that combining natural and agricultural lands maximizes carbon sequestration, highlighting the importance of conserving natural ecosystems within agricultural landscapes for climate mitigation and sustainable development.
11	Symphorien Ongolo & Max Krott. (2025)	General Introduction to the Politics of Global Sustainability in Africa: Power Dynamics in the Forests" (Chapter in the book Power Dynamics in African Forests: The Politics of Global Sustainability)	This study examines the social and environmental consequences of forest conversion in Africa driven by globalization and the rising global demand for commodities such as timber, cocoa, palm oil, and rubber. Through multiple case studies, the book highlights how unequal power relations and weak forest governance hinder sustainable development goals. The findings reveal that both formal and informal practices, as well as power asymmetries between dominant and subordinate actors, play a central role in shaping forest exploitation and conservation across Africa

12	Jing Zhao; Janice Ser Huay Lee; Andrew J. Elmore; Yuti Ariani Fatimah; Izaya Numata; Xin Zhang; Mark A. Cochrane. (2022)	Spatial patterns and drivers of smallholder oil palm expansion within peat swamp forests of Riau, Indonesia	This study analyzes the rapid expansion of smallholder oil palm plantations on peatlands in Southeast Asia, a major driver of tropical peat swamp forest loss since 1990. Using 2019 remote sensing data and logistic regression models, the research identifies roads, proximity to mills, land-use zones, and environmental factors as key determinants of smallholder expansion. Results show that 90% of smallholder plantations are located within 2 km of roads and 25 km of mills. The study highlights these spatial drivers as critical for prioritizing peatland conservation and formulating strategies to curb further deforestation.

Analysis of twelve studies shows palm oil cultivation's strong links to environmental degradation across three main themes: carbon emissions, biodiversity loss, and land use change.

1. Carbon Emissions and Greenhouse Gas Accumulation

Across the reviewed literature, carbon-related impacts of palm oil cultivation represent the most extensively studied dimension. The work by (Kauffman et al., 2025) provided a global quantitative benchmark by measuring carbon stocks in 125 tropical peat forests. Their results show that peat soils constitute approximately 86% of total carbon storage, indicating that peatland conversion to oil palm plantations directly releases massive carbon reserves accumulated over millennia. The study estimates that the social cost of carbon from such conversion is up to nine times higher than the economic return generated from palm oil exports an alarming imbalance highlighting the unsustainable economic logic of peatland exploitation.

Complementing this, (Calderón-Balcázar et al., 2023) found a sharp contrast in biomass and carbon sequestration between natural forests (542 Mg ha^{-1}) and oil palm plantations (285 Mg ha^{-1}) in Colombia's Llanos Orientales. The findings reaffirm that even though palm oil crops store a portion of carbon, they cannot compensate for the extensive carbon loss following deforestation. These results converge with (McGowan et al., 2025), who demonstrated that historical deforestation and plantation expansion in Malaysia have significantly altered carbon sedimentation dynamics in wetlands, revealing human-induced modifications in natural carbon cycles.

Meanwhile, (Okarda et al., 2024) advanced the analysis through modeling, presenting the Simulation of Indonesian Palm Oil Sustainability (SIPOS) system. Their simulations suggest that policy interventions particularly "No Deforestation, No Peat, No Exploitation (NDPE)" commitments and yield intensification can curb emissions without reducing national economic output. This model highlights that sustainability transitions in palm oil are technically feasible when policy, governance, and land management systems operate synergistically.

2. Biodiversity Loss and Ecosystem Disruption

Biodiversity degradation emerges as a consistent environmental consequence of palm oil expansion. The study by (Ahamat & Wong, 2025) emphasizes how inadequate integration between Malaysia's Environmental Quality Act and agricultural regulations exacerbates biodiversity loss through pesticide overuse and habitat destruction. They argue that regulatory fragmentation results in policies that prioritize yield over ecological health.

Similarly, (Purnama et al., 2025) highlight the food-versus-fuel dilemma, where biodiesel expansion accelerates the conversion of forest habitats, driving the extinction of endemic species. The authors note that sustainability certifications such as RSPO (Roundtable on Sustainable Palm Oil) and ISPO (Indonesian Sustainable Palm Oil) often fail to prevent biodiversity degradation due to weak enforcement and voluntary compliance mechanisms.

The ethical dimensions of biodiversity loss are further reflected in (Gotschall et al., 2025), who discuss palm oil derivatives used in emollients and cosmetics. Their analysis links dermatological product manufacturing to deforestation, thus expanding the discourse beyond agriculture into consumer industries. This interdisciplinary approach underscores that biodiversity loss is not confined to agricultural frontiers but embedded in global supply chains and consumption patterns.

Adding a cultural perspective, (Wuntu et al., 2024) interpret environmental degradation through ecocritical analysis of Luka Perempuan Asap, a literary work that allegorically critiques deforestation and pollution resulting from palm oil exploitation.

3. Land Use and Land Cover Transformation

Land use change represents the spatial manifestation of palm oil–related environmental stress. (Zhao et al., 2022) provide a detailed spatial analysis of smallholder expansion across Riau's peat swamp forests. Their findings indicate that over 90% of smallholder plantations are located within 2 km of major roads, underscoring the role of infrastructure in accelerating deforestation. The study also identifies proximity to mills as a crucial driver, implying that industrial clustering amplifies land conversion pressures.

In Africa, (Ongolo & Krott, 2023) explore the political economy of forest transformation, showing how power asymmetries between global commodity demand and local governance perpetuate unsustainable land use. Their research demonstrates that palm oil's environmental footprint is inseparable from structural inequalities within the global sustainability discourse.

The perception dimension explored by (Lieke et al., 2023) adds another layer, showing that Western consumers often associate palm oil simplistically with deforestation without recognizing the nuanced trade-offs involving land productivity and alternative crops. While awareness campaigns can improve understanding, they rarely lead to behavioral change or informed support for sustainable land management initiatives.

Research shows palm oil–driven land use change is globally linked to infrastructure, governance, and consumption, with measures like peatland access limits, mill regulation, and agroforestry buffers key to mitigation.

A notable insight emerging from the SLR is the growing relevance of system-based and interdisciplinary approaches. Quantitative analyses (e.g., Kauffman et al., Calderón-Balcázar et al.) reveal measurable ecological impacts, while modeling studies (Okarda et al.) and socio-political inquiries (Ongolo & Krott) contextualize these effects within broader governance frameworks. Meanwhile, cultural and ethical investigations (Wuntu et al.; Gotschall et al.) expand the epistemic boundary of environmental inquiry beyond natural science, highlighting that sustainability is also a moral and societal pursuit.

Furthermore, emerging technological alternatives such as waste-based biodiesel production identified by (Ali Ijaz Malik et al., 2024) suggest pathways toward decarbonization without increasing land pressure.

DISCUSSION

This section presents findings addressing RQ1 and RQ2, integrating evidence on palm oil's impacts toward carbon emissions, biodiversity loss, and land use change,while examining emerging mitigation strategies and sustainability frameworks.

Environmental Consequences of Palm Oil Cultivation (RQ1)

1. *Carbon Emissions and Greenhouse Gas Dynamics*

Palm oil cultivation has become one of the most intensive anthropogenic contributors to tropical carbon emissions due to its reliance on deforestation and peatland conversion. The reviewed literature consistently indicates that clearing tropical peat forests for oil palm plantations releases enormous quantities of stored carbon accumulated over millennia. Peat depths exceeding seven meters, such as those documented in Indonesia and Malaysia, contain average carbon stocks of over 4,600 Mg C ha^{-1}, of which approximately 86% is stored in soil organic matter (Sarpong et al., 2025). Once these peat layers are drained or burned, they release carbon dioxide and methane at rates that persist for decades, transforming carbon sinks into major emission sources.

Furthermore, post-conversion emissions continue long after plantation establishment. Studies report that drained peatlands experience annual subsidence of 3–5 cm, resulting in continuous oxidation and carbon flux even in mature plantations. Fertilizer application and biomass burning add secondary greenhouse gas sources, particularly nitrous oxide and methane, which amplify the global warming potential of palm oil production. When integrated into life-cycle assessments, the emission footprint of palm oil-derived biodiesel often rivals or surpasses that of fossil fuels unless strict sustainability criteria are met (Cisneros et al., 2024).

Spatial analyses have further revealed that smallholder-driven expansion in peat swamp forests is particularly problematic. Approximately 90% of new plantations are located within 2 km of access roads and 25 km of processing mills, underscoring the infrastructure deforestation nexus (Jong et al., 2021). These findings suggest that accessibility factors, rather than agronomic suitability alone, drive spatial patterns of carbon-emitting land conversion.

At the macro level, tropical peatland conversion for palm oil accounts for nearly 10% of total global deforestation-related emissions. Cumulatively, these emissions contribute significantly to the regional carbon budget, exacerbating climate instability. The reviewed evidence thus highlights a critical paradox: while palm oil serves as an economically efficient crop, its climate cost measured through the social cost of carbon often exceeds its financial return (VanderWilde et al., 2023).

2. Biodiversity Loss and Ecological Fragmentation

Parallel to its carbon implications, palm oil expansion has precipitated severe biodiversity degradation across tropical ecosystems. Primary forests converted into monoculture plantations lose structural and compositional complexity, resulting in the collapse of trophic networks. Comparative ecological studies show that oil palm landscapes host less than half the vertebrate and invertebrate species richness found in adjacent intact forests (Fleiss et al., 2023). Keystone species such as orangutans, hornbills, and tigers face habitat fragmentation, isolation, and heightened extinction risk.

Fragmentation also reduces genetic exchange between populations, eroding long-term ecosystem resilience. Research from Borneo and Sumatra indicates that species with limited dispersal capacity such as forest-dependent birds and amphibians are disproportionately affected (Mardiatmoko, 2023).

The social dimension of biodiversity loss further complicates the picture. Indigenous communities that depend on forest resources for livelihood and cultural identity face declining ecosystem services and resource scarcity. Thus, biodiversity degradation is not merely an ecological issue but also a social justice concern (Murphy, 2023).

3. Land Use Change and Landscape Transformation

Land use change (LUC) serves as the underlying mechanism linking carbon emissions and biodiversity loss. The reviewed literature identifies Southeast Asia as the epicenter of rapid agricultural transformation driven by global demand for palm oil. Over the past three decades, Indonesia and Malaysia have collectively converted millions of hectares of forest into plantation estates.

Geospatial analyses reveal that oil palm expansion often follows a sequential trajectory: initial clearing of primary forest, short-term use for timber extraction, and eventual conversion into plantation land. The loss of forest canopy increases surface temperatures, reduces evapotranspiration, and elevates local drought risk (Sakai et al., 2022).

Indirect land use change (ILUC) further amplifies these impacts. When traditional agricultural lands are displaced by industrial-scale plantations, smallholders frequently clear new forest areas elsewhere, creating a cycle of deforestation leakage. Consequently, the overall landscape experiences a systemic ecological reconfiguration, characterized by homogenization and decreased ecological resilience.

Land use change is also associated with soil erosion, nutrient depletion, and water contamination. The sedimentation of nearby rivers and wetlands undermines water quality, affecting downstream ecosystems and communities. In Malaysia, for instance, lake sediment cores have recorded a sharp rise in organic carbon accumulation since the 1940s, corresponding with plantation and mining activities (Jupesta et al., 2022).

Mitigation Strategies and Theoretical Approaches (RQ2)

1. Sustainability Certification and Policy Interventions

In response to the documented environmental consequences, the palm oil industry and policymakers have developed a series of sustainability frameworks. The most prominent are the Roundtable on Sustainable Palm Oil (RSPO) and the Indonesian Sustainable Palm Oil (ISPO) certification systems, both designed to promote compliance with environmental and social standards.

However, systematic reviews reveal that these schemes often face limitations in scope and enforcement. Certification coverage remains partial, primarily encompassing large industrial estates while excluding numerous smallholders. Moreover, audits frequently rely on self-reporting and lack independent verification mechanisms. As a result, the environmental benefits of certification such as reduced deforestation or improved carbon management are often modest (Jaroenkietkajorn & Gheewala, 2021).

Beyond certification, national and international policies have sought to strengthen environmental governance. The "No Deforestation, No Peat, No Exploitation" (NDPE) commitments, adopted by several major producers, aim to decouple economic growth from ecological degradation. Dynamic modeling tools, such as the Simulation of Indonesian Palm Oil Sustainability (SIPOS), demonstrate that integrating NDPE policies with intensification strategies can reduce emissions while maintaining economic output (Batsi et al., 2021).

2. Technological and Land Management Innovations

Technological innovation, including precision farming and satellite monitoring, enhances transparency and accountability by improving detection of deforestation and land-use violations..

Equally important are landscape-level strategies such as peatland restoration, rewetting, and the establishment of ecological corridors. Rewetting of drained peatlands can significantly reduce carbon flux by restoring anaerobic conditions, whereas reforestation with native species supports biodiversity recovery. Agroforestry integration combining oil palm with other crops or forest species has also been proposed as a transitional model to enhance ecological diversity and soil stability (Schmidt & De Rosa, 2020).

Moreover, the promotion of waste-based biodiesel feedstocks, such as used cooking oil and animal fats, offers a viable alternative to land-intensive palm oil production (Abeln & Chuck, 2021). These approaches align with circular economy principles and reduce the dependency on virgin land conversion, thereby mitigating both carbon and biodiversity impacts.

3. Theoretical Integration: Ecological Modernization and Environmental Kuznets Curve

The evidence aligns with Ecological Modernization Theory and the Environmental Kuznets Curve, suggesting that innovation, reform, and responsible governance can drive sustainable palm oil production while supporting economic growth.

Conversely, the EKC hypothesis posits an inverted-U relationship between economic growth and environmental degradation: impacts intensify during early development stages but decline once income levels and environmental awareness increase (Dewi, 2021). Palm oil-producing nations appear to be navigating this trajectory, wherein economic expansion initially accelerates degradation but emerging sustainability measures may eventually trigger ecological stabilization.

Integrating EKC and EMT offers a holistic view: current degradation reflects early development stages, while innovation and policy reform drive progress toward sustainable palm oil through economic and institutional maturity.

4. Socioeconomic and Ethical Dimensions of Sustainability

Palm oil sustainability goes beyond the environment, requiring fair labor, equity, and respect for indigenous rights, with governance that integrates social inclusion and ethical responsibility.

Public perception also plays a critical role. Consumer awareness campaigns in importing countries influence global demand for certified palm oil, yet misconceptions persist. Many consumers associate palm oil solely with deforestation while overlooking its higher yield efficiency compared to other oil crops (Deviany & Chaerun, 2024). Enhancing consumer literacy and transparency in supply chains can thus reshape global market incentives toward sustainable production.

Mitigation strategies must therefore adopt an integrated landscape approach that combines ecological, economic, and social dimensions. The synthesis of reviewed studies suggests three key policy implications:

1. Strengthening Multi-Level Governance: Effective sustainability requires coherent policies that bridge national regulations, corporate commitments, and local enforcement. Fragmented governance structures currently undermine compliance and monitoring capacity.
2. Promoting Technological Transparency: Advanced remote-sensing technologies and open-access spatial data can enhance traceability across supply chains, ensuring that production aligns with zero-deforestation pledges.
3. Reframing Economic Incentives: Incorporating the social cost of carbon into fiscal and trade policies can internalize environmental externalities, encouraging producers to adopt sustainable practices.

This review affirms that ecological modernization and economic growth can align, with sustainable palm oil achievable through adaptive governance, innovation, and global cooperation.

CONCLUSIONS AND RECOMMENDATIONS

Palm oil expansion in peatlands and forests drives carbon emissions, biodiversity loss, and land degradation. Stronger governance, accountability, and landscape-based practices are crucial to reducing impacts and achieving sustainable production.

ADVANCED RESEARCH

This advanced research analyzes 12 recent studies on palm oil cultivation, revealing that peatland conversion and deforestation cause major carbon emissions, biodiversity loss, and land use change. While sustainability policies like RSPO and NDPE offer partial solutions, weak enforcement limits their impact. The study concludes that sustainable palm oil production requires stronger governance, innovation, and global cooperation to balance economic growth with environmental protection.

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