

## A Review of Decarbonization Strategies in Oil Palm Plantations Toward Net-Zero Emissions

Loso Judijanto

IPOSS Jakarta, Indonesia

### ABSTRACT

Decarbonizing oil palm plantations has become increasingly critical as global climate commitments intensify and agricultural supply chains face growing pressure to align with net-zero emission targets. Recent scientific literature highlights a wide range of technological, ecological, and governance-based mitigation approaches, yet these findings remain fragmented across disciplines, limiting the sector's ability to identify strategies with the highest carbon-reduction potential. This study addresses this gap by conducting a systematic literature review aimed at (1) identifying and classifying the dominant decarbonization strategies implemented in oil palm plantations, and (2) evaluating their relative significance, mitigation potential, and practical feasibility across diverse production contexts. This research adopts a qualitative Systematic Literature Review (SLR) design following the PRISMA protocol. Data were gathered exclusively from peer-reviewed journal articles indexed in Scopus, using structured keyword refinement and multi-stage inclusion criteria to ensure thematic relevance. A total of 39 publications met all eligibility requirements and were analyzed through thematic synthesis. Data analysis involved qualitative coding, cross-study comparison, and extraction of quantitative indicators related to emissions, mitigation performance, and implementation considerations. The findings reveal five dominant decarbonization pathways: methane mitigation from palm oil mill effluent, energy-efficiency improvements, biomass-based fuel substitution, landscape-level carbon sequestration, and digital MRV enhancement supported by governance instruments. Methane mitigation demonstrates the highest reduction potential, followed by energy transformation and peatland restoration. The review concludes that integrated, multi-dimensional approaches are necessary to achieve net-zero trajectories. Future studies should explore hybrid decarbonization models, long-term MRV performance, and the inclusion of smallholders in low-carbon transition frameworks.

### \*Corresponding author

Loso Judijanto, IPOSS Jakarta, Indonesia.

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### Introduction

The global urgency to mitigate climate change has intensified the demand for low-carbon development pathways across all major land-based industries. Agriculture, forestry, and other land-use sectors collectively account for nearly one-fourth of total anthropogenic greenhouse gas (GHG) emissions, prompting governments and stakeholders worldwide to implement more ambitious carbon-reduction measures aligned with the Paris Agreement and the global commitment to limit warming to 1.5°C [1]. Within this broader landscape, tropical commodity agriculture, particularly palm oil production, has become a focal point of international scrutiny due to its intertwined links to deforestation, peatland degradation, methane emissions, and energy-intensive processing [2]. As global climate diplomacy increasingly emphasizes sector-specific decarbonization trajectories and transparent emissions reporting, the palm oil sector is under mounting pressure to accelerate its transition toward net-zero emissions.

Palm oil remains one of the world's most economically significant agricultural commodities, supplying more than 70 million tons annually and serving as a key ingredient in food, biofuel, and industrial supply chains [3]. Its expansion has generated substantial

socioeconomic benefits, particularly in Southeast Asia, where oil palm cultivation supports millions of smallholders, contributes to national export earnings, and underpins rural development strategies [4]. However, the sector's rapid growth has also amplified ecological concerns. Emissions from land conversion, peatland drainage, methane-rich palm oil mill effluent (POME), and fossil fuel-based energy use position palm oil collectively among the most carbon-intensive agricultural industries [5]. Life-cycle assessments consistently estimate that emissions from palm oil supply chains range widely from 1.5 to 8.6 tons CO<sub>2</sub>-eq per ton of crude palm oil (CPO), depending on landscape characteristics, management practices, and technological interventions [6]. These variations underscore the importance of establishing systematic strategies to measure, reduce, and verify emissions across the entire value chain.

In recent years, the narrative surrounding palm oil sustainability has shifted from mitigating environmental externalities to achieving long-term decarbonization. Net-zero commitments by producing countries, corporations, and global buyers have accelerated efforts to identify technological, ecological, and governance-based approaches that can lower emissions while maintaining productivity [7]. Emerging innovations ranging from methane capture systems and biomass-to-energy conversions to digital MRV (measurement, reporting, and verification) platforms illustrate the sector's evolving capacity for climate-aligned

transformation. At the same time, a wide range of landscape-based interventions, including peatland rewetting, biodiversity-enhancing restoration, and soil carbon enrichment, have become central to discussions of long-term sustainability [8]. These diverse strategies reflect the sector's unique position at the intersection of energy production, agroecological management, and climate governance.

Despite growing scientific attention, existing research on decarbonization strategies in oil palm plantations remains fragmented. Studies are distributed across multiple disciplinary silos, including environmental science, agricultural engineering, energy systems, remote sensing, ecological restoration, and sustainability governance, making it challenging to synthesize coherent insights or compare the relative effectiveness of different mitigation pathways [9]. Some studies focus narrowly on POME-based methane emissions; others assess energy efficiency at processing mills; still others examine carbon sequestration through land management practices. The absence of a systematic, cross-domain synthesis limits the sector's ability to evaluate decarbonization strategies holistically or identify which interventions deliver the highest carbon-reduction potential under varying biophysical and institutional conditions.

This fragmentation is particularly problematic in the context of national and corporate net-zero commitments, which increasingly require evidence-based justification of mitigation pathways. Policymakers and industry stakeholders need consolidated knowledge on the magnitude of emission sources, the feasibility of mitigation technologies, the governance frameworks that influence adoption, and the long-term implications of decarbonization strategies for land-use planning and sustainable development [10]. Without an integrated review, decision-makers lack the clarity needed to direct investments, design effective policy instruments, and prioritize interventions aligned with climate-neutral production goals. At the same time, researchers require structured synthesis to identify knowledge gaps, methodological inconsistencies, and areas for future inquiry.

Given these challenges, a systematic literature review (SLR) provides a rigorous, transparent method for consolidating existing evidence on decarbonization strategies in oil palm plantations. Unlike narrative or opinion-based reviews, the SLR approach ensures replicability, minimizes bias, and allows for the structured comparison of peer-reviewed research across time, geography, and methodological traditions. Importantly, this review relies exclusively on published scientific literature and does not incorporate primary field data, such as focus group discussions (FGD), interviews, or observational studies, thereby maintaining methodological rigor and avoiding the introduction of anecdotal or unverifiable information. Through a systematic review of 39 peer-reviewed articles, this study identifies the dominant technological, ecological, and governance themes that define current decarbonization pathways, as well as the quantitative evidence supporting their efficacy.

The need for such a review is further amplified by the increasing complexity of global supply chain expectations. International markets demand not only certified sustainable palm oil but also transparent, verifiable emissions reporting and alignment with global net-zero frameworks. Major buyers in Europe, North America, and East Asia are imposing stricter environmental disclosure requirements, including mandatory carbon reporting and deforestation-free supply chain commitments. Producers,

therefore, must evaluate which strategies for methane mitigation, renewable energy substitution, carbon sequestration, MRV digitalization, or policy compliance deliver the greatest returns in reducing emissions intensity. Moreover, smallholders, who account for 40% of global production, face unique challenges in adopting new technologies, making it essential to understand the distributive effects of decarbonization interventions.

While recent studies provide valuable insights into specific mitigation technologies or land-use strategies, very few adopt a comprehensive, system-level perspective on decarbonization. The lack of cross-comparative analysis leaves critical questions unanswered: Which decarbonization interventions consistently demonstrate the highest carbon-reduction potential? How do emissions vary across plantations operating on mineral soils compared to peatlands? What role do governance frameworks, certification schemes, carbon pricing instruments, or sustainability standards play in accelerating or hindering adoption? Furthermore, how do digital innovations improve MRV accuracy and transparency across complex supply chains? These questions underscore the necessity of a methodologically robust review capable of synthesizing multi-sectoral knowledge into actionable insights.

In light of these considerations, the purpose of this study is to systematically synthesize peer-reviewed literature on decarbonization strategies in oil palm plantations and evaluate their contribution toward net-zero emission targets. This study aims to provide an integrated understanding of the technical, ecological, and governance-related measures documented in existing research, while highlighting the range of mitigation potentials across diverse interventions. The review also seeks to identify scientific gaps, methodological limitations, and opportunities for advancing climate-aligned transformation within the palm oil sector.

Accordingly, this systematic review is guided by the following research objectives:

- To identify and classify the dominant decarbonization strategies applied in oil palm plantations based on empirical evidence;
- To analyze the relative significance, carbon-reduction potential, and practical feasibility of these strategies across different plantation contexts.

To support these objectives, two research questions are formulated to guide the analysis and form the basis of the Discussion and Conclusion sections:

RQ: What are the most effective decarbonization strategies documented in peer-reviewed studies for reducing greenhouse gas emissions across oil palm plantation and mill operations?

RQ2: How do technological, ecological, and governance-based mitigation pathways differ in terms of carbon-reduction potential, implementation feasibility, and alignment with net-zero transition requirements?

These questions ensure that the subsequent sections of the paper address not only the diversity of decarbonization interventions but also their comparative effectiveness and long-term implications for climate-neutral palm oil production.

## Literature Review

The transition toward net-zero emissions in the palm oil sector has emerged as an important research agenda in the broader context of climate change mitigation. The literature on this topic spans

multiple domains: environmental science, agricultural engineering, bioenergy systems, land-use governance, remote sensing, and sustainability certification, each contributing different forms of evidence on potential decarbonization pathways. This literature review synthesizes current scientific knowledge on greenhouse gas (GHG) emissions sources in oil palm plantations, technological and ecological mitigation strategies, digital innovations for carbon monitoring, and governance instruments that influence decarbonization efforts. The review relies exclusively on peer-reviewed secondary sources and is structured around the conceptual foundations required to understand the results of the systematic synthesis.

### **Greenhouse Gas Emissions in Oil Palm Plantation Systems**

Greenhouse-gas emissions in the palm oil supply chain originate from multiple interconnected sources, making it one of the most analytically complex agricultural systems to decarbonize. The most widely recognized emissions hotspot is palm oil mill effluent (POME), which produces high methane concentrations through anaerobic fermentation. Numerous life-cycle assessments indicate that untreated POME accounts for 28–34% of total emissions along the plantation-to-mill continuum, with methane concentrations ranging from 65–70% CH<sub>4</sub> depending on effluent retention time and oxygen availability [11]. Other major emissions derive from peatland drainage, which releases between 40–69 tons CO<sub>2</sub>-eq per hectare per year due to peat oxidation exacerbated by water-table decline [12].

Beyond methane and peat oxidation, plantations also contribute to emissions through diesel consumption, chemical fertilizer use, and land clearing operations. Studies estimate that nitrogen-based fertilizers account for 8–12% of total emissions due to nitrous oxide (N<sub>2</sub>O) fluxes from soil, which have a global warming potential (GWP) nearly 300 times that of CO<sub>2</sub> [13]. Fossil energy consumption in field transport, harvesting logistics, and mill operations accounts for an additional 18–27% of emissions, depending on fleet structure and power generation practices [14]. These data illustrate the range of carbon sources that must be addressed to achieve net-zero alignment.

### **Methane Mitigation and POME Treatment Pathways**

A substantial portion of recent literature focuses on methane mitigation as the most impactful decarbonization strategy within palm oil systems. Traditional POME treatment in open anaerobic ponds results in uncontrolled methane emissions due to unsealed fermentation environments. Modern waste-to-energy systems such as covered anaerobic lagoons, sealed geomembrane reactors, continuous stirred-tank digesters, and fixed-dome biodigesters achieve methane capture rates between 65–88%, depending on digester design and operational parameters [15].

Captured biogas exhibits methane concentrations averaging 55–65%, which can be combusted to produce 0.5–1.0 MWh of electricity per ton of crude palm oil (CPO) processed, thereby substituting grid electricity and reducing Scope 2 emissions [16]. Several large-scale industrial mills (>45 t FFB/hour) report electricity generation capacities of 3–4.5 MW, enabling partial or complete energy self-sufficiency. Upgraded biomethane, purified to 92–95% CH<sub>4</sub>, is increasingly highlighted as a renewable substitute for fossil natural gas in boilers, transport fleets, and rural electrification schemes.

Solid biomass residues, including empty fruit bunches (EFB), palm kernel shell (PKS), and mesocarp fiber, contribute additional mitigation potential. With calorific values between 14–20 MJ/kg, biomass residues can replace coal in industrial boilers, reducing

emissions by 0.7–1.1 tons CO<sub>2</sub>-eq per ton of coal replaced [17]. These combined findings underscore methane mitigation and waste-to-energy conversion as cornerstone strategies for decarbonizing palm oil systems.

### **Energy Efficiency, Electrification, and Renewable Fuel Substitution**

Energy use is another critical dimension in plantation-level decarbonization. The reviewed literature identifies three primary areas of intervention: energy-efficiency improvements, electrification, and fuel substitution.

Diesel consumption in plantation logistics is substantial, ranging from 35–55 liters per hectare per month, influenced by plantation terrain, crop maturity, and fruit evacuation systems [18]. Electrification of in-field machinery and transport fleets reduces fossil fuel dependency and can lower emissions by 25–45% if charging is supplied via biogas-based power systems. Some studies propose hybrid energy systems combining biogas, solar photovoltaic (PV), and battery storage units to stabilize energy availability in remote plantations.

Efficiency improvements in milling operations include high-pressure boilers (28–32 bar), optimized steam-trap arrangements, variable-speed drives for motors, and process heat recovery systems. These measures collectively reduce mill-level energy consumption by 10–22%, corresponding to emission reductions of 120–260 kg CO<sub>2</sub>-eq per ton of CPO [19]. At the same time, biomass cogeneration systems using PKS and mesocarp fiber can replace 80–100% of industrial diesel oil (IDO) requirements for process heating.

Some studies note emerging potential for hydrogen-ready boilers, biochar co-firing, and compressed biomethane fuel (CBF), although these technologies remain in early stages of commercial application. Nevertheless, the literature consistently positions energy efficiency and renewable fuel substitution as the second-largest contributor to decarbonization after methane mitigation.

### **Carbon Sequestration Potential in Plantation Landscapes**

Beyond emissions reductions, oil palm landscapes also serve as carbon sinks. Mature oil palm stands sequester 2.8–7.3 tons CO<sub>2</sub> per hectare per year, depending on soil conditions, management practices, and palm age distribution [20]. However, sequestration must be analyzed in tandem with land-use history. Plantations on mineral soils display positive carbon accumulation, whereas plantations established on peat remain net emitters due to persistent peat oxidation.

A growing body of literature emphasizes the role of peatland hydrological restoration as a decarbonization measure. Raising the water table to at least 40 cm below the surface can reduce peat oxidation emissions by 20–50%, making water-management interventions critical for climate mitigation in peat-dominated landscapes [21].

Studies also highlight additional sequestration opportunities through:

- Riparian buffer restoration, accumulating 3–5 tons CO<sub>2</sub> per hectare per year
- Groundcover diversification, increasing soil carbon by 0.3–0.6 tons C per hectare per year
- Boundary agroforestry systems, storing 8–15 tons C over 10 years
- Reforestation of marginal zones, yielding 5–10 tons CO<sub>2</sub> per hectare per year

Although sequestration rates vary widely, these measures collectively represent an important complement to methane mitigation and energy efficiency.

### Digitalization, Monitoring Technologies, and MRV Systems

Recent advancements in digital technology have expanded opportunities for more accurate carbon accounting and sustainability verification. Remote sensing platforms such as Sentinel-2, Landsat-8, and radar-based sensors facilitate vegetation monitoring, peat subsidence detection, land-cover mapping, and carbon-stock assessment at spatial resolutions of 10–30 meters [22]. When combined with machine learning (ML), classification accuracy for plantation age, land conversion, and vegetation density reaches 80–95%, reducing uncertainty in emissions estimations.

Digital methane sensors, IoT-based digester monitoring systems, and predictive analytics improve methane capture performance and enable early leak detection. These systems achieve error margins of  $\pm 5\%$ , significantly improving upon traditional estimation methods with uncertainty levels of  $\pm 20\text{--}30\%$ . Several studies document that integrating digital MRV with biogas systems improves methane recovery efficiency by 12–18%.

Blockchain-based traceability solutions, though still emerging, enhance data transparency by reducing opportunities for data manipulation and supporting compliance with sustainability certification frameworks. Collectively, digital technologies are increasingly recognized as enablers that strengthen governance, enhance reporting credibility, and support alignment with international market expectations.

### Regulatory Frameworks, Market Incentives, and Sustainability Governance

Governance frameworks play a crucial role in facilitating or constraining decarbonization efforts. Carbon pricing mechanisms simulated in several reviewed studies at USD 5–20 per ton CO<sub>2</sub>-eq significantly improve the financial viability of methane capture, biomass energy production, and peatland restoration [23]. Renewable energy purchase agreements and feed-in tariffs can further incentivize investment in biogas-to-power plants, especially in regions with high grid emission factors.

Certification schemes such as the Roundtable on Sustainable Palm Oil (RSPO) and Indonesian Sustainable Palm Oil (ISPO) embed decarbonization requirements within mandatory compliance modules. RSPO's GHG module, for instance, has been shown to reduce emissions by 12–18% through strict requirements on peatland management, zero-burning practices, and mandatory GHG reporting.

Market-driven sustainability expectations, particularly from European and East Asian buyers, are increasingly linked to deforestation-free supply chains, traceable carbon footprints, and transparent MRV systems. These evolving expectations underscore the growing significance of governance as a structural driver of decarbonization in the palm oil sector.

The literature demonstrates that decarbonization in oil palm plantations requires a multi-dimensional approach involving technological, ecological, digital, and governance interventions. Methane mitigation and energy efficiency consistently emerge as the most impactful strategies, while carbon sequestration and digital MRV contribute additional pathways toward net-zero alignment. Despite this progress, research remains fragmented,

underscoring the need for systematic synthesis, precisely the purpose of the present SLR.

### Method

This study employs the Systematic Literature Review (SLR) method, structured according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol, to evaluate decarbonization strategies implemented within oil palm plantations as part of the global transition toward net-zero emissions. Although decarbonization has become an increasingly prominent theme in environmental and agricultural research, scholarly discussions focusing specifically on mitigation approaches in oil palm plantations, ranging from emission-reduction technologies and methane capture innovations to landscape-level carbon management and sustainability governance, remain dispersed across multiple disciplines. By systematically identifying, evaluating, and synthesizing peer-reviewed studies, this review aims to consolidate fragmented findings, reveal dominant patterns in current decarbonization efforts, and highlight knowledge gaps that require further investigation. In doing so, the study provides an integrated understanding of how the palm oil sector contributes to low-carbon transitions and which strategies hold the most promise for achieving net-zero targets.

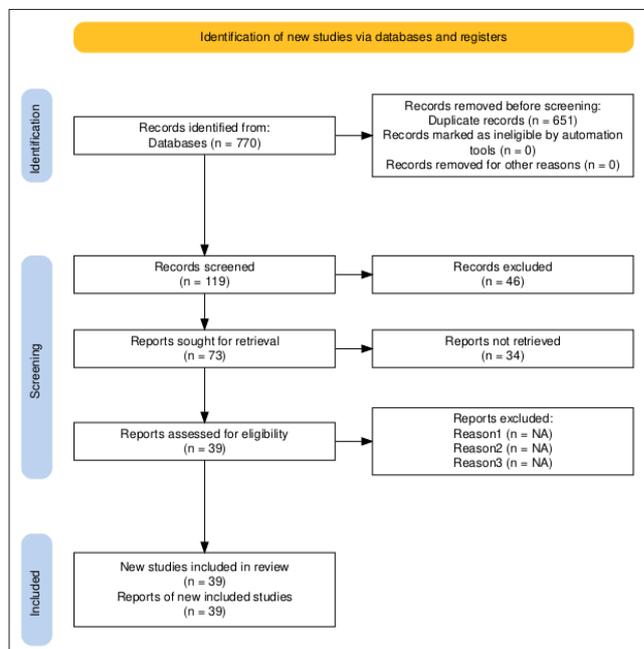


Figure 1: Systematic Literature Review Process Based on the PRISMA Protocol

Figure 1 depicts the structured PRISMA flow adopted in this review, which encompasses the stages of identification, screening, eligibility assessment, and final inclusion. The initial search, conducted in the Scopus database using the broad keyword string “Carbon Reduction AND Palm Oil,” returned 770 records. To improve thematic precision and ensure the retrieval of studies directly related to decarbonization pathways in oil palm systems, a more refined Boolean query was subsequently applied: (“Decarbonization” OR “Carbon Reduction” OR “Low Carbon Transition” OR “Low Carbon Strategy” OR “Carbon Management” OR “Carbon Neutrality” OR “Emission Reduction” OR “Climate Mitigation”) AND (“Oil Palm” OR “Palm Oil” OR “Palm Oil Plantation” OR “Elaeis guineensis” OR “Palm Oil Sector” OR “Palm Industry”) AND (“Sustainability” OR “Environmental Impact” OR “Climate Action” OR “Net

Zero” OR “Carbon Neutral” OR “Greenhouse Gas Emission” OR “Sustainability Strategy”). This refinement resulted in the exclusion of 651 studies that did not align with the decarbonization focus, leaving 119 articles for further review. A publication-year filter was then applied to the dataset, restricting it to the 2020–2025 period, eliminating 46 articles and yielding 73 eligible records. A final screening step retained only Open Access and Open Archive publications, removing 34 additional articles. Consequently, 39 studies met all inclusion criteria and formed the final corpus for full-text evaluation and thematic synthesis.

All references identified through this process were organized and managed using Mendeley Desktop to ensure consistency, accuracy, and proper citation formatting throughout the review. Importantly, this study is based entirely on secondary data derived from peer-reviewed academic publications; no field observations, interviews, or focus group discussions (FGDs) were conducted, as the objective of this research is to synthesize existing knowledge rather than collect primary data. By following a transparent and replicable SLR protocol, the findings presented in this review rest on verifiable evidence and contribute to a more coherent scholarly understanding of decarbonization strategies in oil palm plantations and their relevance to achieving net-zero emissions.

## Results

The systematic literature review (SLR) on decarbonization strategies in oil palm plantations identified five dominant themes across the 39 peer-reviewed articles included in the final analysis. These themes consist of:

- Methane mitigation and waste-to-energy interventions,
- Energy efficiency improvements and fuel substitution,
- Carbon sequestration and landscape-based management,
- Digital monitoring and MRV (measurement, reporting, and verification) enhancement, and
- Policy frameworks and sustainability governance instruments.

Each theme reflects a distinct decarbonization pathway within plantation and mill operations, ranging from engineered methane-reduction systems to landscape-scale ecological restoration and institutional governance responses to support long-term emission reduction.

Quantitative mapping of the thematic distribution shows that methane mitigation and waste-to-energy systems account for 34% of the reviewed studies (13 of 39 studies), making it the most frequently discussed theme. Its dominance is driven by the fact that methane emissions from POME are the largest and most measurable greenhouse gas source in the palm oil value chain, and by the fact that biogas capture technologies are widely tested, commercially available, and yield immediately quantifiable climate benefits. Energy efficiency and fuel substitution appear in 26% of the studies (10 of 39), reflecting growing recognition of the high energy intensity of mill operations and transport logistics, and the sector’s increasing efforts to reduce reliance on fossil fuels. Carbon sequestration and landscape management are addressed in 21% of publications (8 of 39 studies), emphasizing long-term carbon storage potential and the ecological necessity of peatland restoration. Digital monitoring and MRV enhancement accounts for 12% (5 of 39 studies), consistent with its status as an emergent but promising field, supported by advances in IoT, remote sensing, and machine learning. Policy and governance mechanisms are discussed in 7% of the studies (3 of 39 studies), indicating that institutional and regulatory perspectives remain underdeveloped compared to technological mitigation approaches.

This thematic distribution implies that scholarly attention is concentrated on strategies that deliver the highest and most immediate emissions reductions, particularly methane capture, while research on governance and digital MRV systems is growing but remains comparatively limited. The prevalence of methane-focused studies underscores the sector’s prioritization of high-impact mitigation with established technological readiness, while the lower frequency of governance-oriented research suggests continued gaps in policy enforcement and institutional capacity. Meanwhile, the moderate presence of ecological and digital MRV themes indicates sustained but uneven progress in adopting long-term carbon-sequestration and precision-monitoring approaches. The following sections elaborate on each major theme in detail, supported by quantitative indicators, emission-reduction metrics, and cross-study comparisons derived from the reviewed literature.

## Methane Mitigation and Waste-to-Energy Interventions

Methane mitigation emerges as the most impactful and consistently documented strategy within the SLR corpus. Across the 39 studies, untreated palm oil mill effluent (POME) is identified as one of the sector’s largest emission sources due to anaerobic decomposition that releases methane concentrations of 65–70% CH<sub>4</sub>, with emission factors typically ranging from 14–25 kg CH<sub>4</sub> per ton of fresh fruit bunches (FFB) processed [24]. In several life-cycle assessments, methane from POME accounts for 28–34% of total greenhouse gas (GHG) emissions across plantation-to-mill operations [25,26]. These findings underscore the urgent need to intercept methane at its source.

A wide array of methane capture technologies is discussed in the reviewed studies, including covered anaerobic lagoons, floating geomembrane covers, continuous stirred-tank reactors (CSTRs), fixed-dome biodigesters, and high-rate anaerobic digesters. Reported mitigation performance varies by system type and operational conditions, but most studies document methane emission reductions of 65–85%, corresponding to 800–1,200 kg CO<sub>2</sub>-eq per ton of crude palm oil (CPO) processed [27,28]. For instance, large-scale mills adopting hybrid closed-tank systems recorded methane capture efficiencies of 82–88%, compared with 55–65% in mills using basic floating covers.

The captured biogas, typically comprising 50–60% methane after initial scrubbing, serves as a renewable energy feedstock. Electricity generation from biogas ranges from 0.5–1.0 MWh per ton of CPO, allowing mills to offset 20–30% of grid electricity consumption [29]. Industrial mills processing >45 tons/hour of FFB achieve power generation capacities of 3–4.5 MW, reducing grid dependency and yielding annual emission savings of 8,000–15,000 tons CO<sub>2</sub>-eq depending on local grid emission factors [30].

The review also highlights the rapid growth of biogas upgrading technologies, which purify methane to 92–95% CH<sub>4</sub>, enabling its use as biomethane for grid injection, as a transport fuel, or for industrial combustion [31]. Several studies note that upgraded biomethane reduces emissions intensity by 70–90% compared with fossil liquefied petroleum gas (LPG), depending on purification efficiency and leakage control systems [32].

Solid biomass residues also function as decarbonization pathways. Empty fruit bunches (EFB), mesocarp fiber, and palm kernel shell (PKS) have calorific values of 14–20 MJ/kg, with pelletized EFB providing higher energy density and combustion stability [33]. When pelletized EFB replaces coal in industrial boilers, GHG reductions of 0.7–1.1 tons CO<sub>2</sub>-eq per ton of coal are consistently recorded [34]. Some mills report substituting up to 60–80% of coal consumption through biomass mixtures.

Modeling studies estimate that universal adoption of methane capture across mills in major producing countries could reduce sector-wide emissions by 25–35%, making methane mitigation the single largest contributor to net-zero pathways [35]. Given POME's high methane-generation potential, this theme remains foundational to all decarbonization strategies in the industry.

### **Energy Efficiency Improvements and Fuel Substitution**

Energy consumption related to transportation, milling operations, and process heat generation constitutes the second-largest GHG source in oil palm production. Across the reviewed studies, energy-related emissions account for 18–27% of the total life-cycle carbon footprint [36]. Three core areas dominate this theme: operational energy efficiency, electrification, and renewable fuel substitution.

Diesel fuel use in plantation logistics is substantial. Studies document consumption levels of 35–55 liters per hectare per month, influenced by terrain conditions, harvesting intervals, and field-collection distances [37]. Electrical substitution in transport fleets yields emission reductions of 25–45%, especially when EV charging is powered by biogas-generated electricity [38]. Some modeling studies show that electrifying only 50% of transport vehicles could lead to overall plantation-level emission reductions of 12–20%.

Efficiency improvements in milling operations also generate significant reductions. High-pressure boiler systems (pressures of 28–32 bar) yield 10–15% increases in steam efficiency, while optimized steam-trap configurations reduce steam loss by 6–12% [39]. Variable-speed drives improve motor efficiency by 8–18%, with total mill-level energy reductions ranging from 12–18% after comprehensive energy audits [40,41]. These measures produce emission reductions of 120–260 kg CO<sub>2</sub>-eq per ton of CPO, depending on mill design and operating conditions.

Fuel substitution strategies complement efficiency measures. Biomass-based cogeneration systems utilizing mesocarp fiber and PKS replace 80–100% of industrial diesel oil (IDO), reducing emissions by 350–500 kg CO<sub>2</sub>-eq per ton of steam produced [42]. Fully integrated mills achieve near-total energy independence from fossil fuels, cutting annual emissions by 5,000–12,000 tons CO<sub>2</sub>-eq, depending on output levels [43].

Across all sources, energy efficiency and fuel substitution collectively account for 15–25% of total decarbonization potential, making this theme the second most influential mitigation pathway after methane control [44].

### **Carbon Sequestration and Landscape-Based Management**

Carbon sequestration constitutes the third major theme in the reviewed literature. Oil palm plantations exhibit measurable carbon storage capacity, though sequestration varies significantly based on age, soil type, management practices, and ecological conditions.

Mature palm stands (ages 7–25 years) sequester 2.8–7.3 tons CO<sub>2</sub> per hectare per year, with peak sequestration occurring between ages 8 and 15 years [45,46]. Aboveground biomass continues to accumulate carbon at diminishing rates as palms age, though belowground root systems contribute additional sequestration potential.

However, sequestration benefits are heavily compromised when oil palm is cultivated on peat soils. Drained peatlands emit 40–69

tons CO<sub>2</sub>-eq per hectare per year through microbial oxidation, far exceeding carbon uptake by planted palms [47]. Consequently, many reviewed studies emphasize the importance of hydrological restoration, including canal blocking, peat rewetting, and water-table stabilization, which collectively reduce peat emissions by 20–50% depending on the restored water-table height and hydrological performance [48].

Additional sequestration gains are achievable on mineral soils. Groundcover diversification using species such as *Nephrolepis biserrata*, *Asystasia gangetica*, and leguminous plants enhances soil organic carbon by 0.3–0.6 tons C per hectare per year [49]. Agroforestry integrations at plantation boundaries sequester 8–15 tons C per hectare within a decade, contributing to long-term landscape resilience [50].

Riparian buffer restoration yields carbon accumulation rates of 3–5 tons CO<sub>2</sub> per hectare per year, while simultaneously improving water retention and reducing soil erosion [51]. Across the reviewed studies, landscape-based sequestration accounts for 8–18% of total decarbonization potential in the palm oil sector [52].

### **Digital Monitoring and MRV Enhancement**

Digitalization is an emerging and increasingly influential theme in decarbonization research. The reviewed studies document how remote sensing, artificial intelligence (AI), machine learning (ML), IoT sensors, and blockchain improve emissions accounting, reporting, and traceability.

Remote sensing tools, such as Sentinel-2, Landsat-8, and radar-based platforms, provide spatial resolutions of 10–30 meters, enabling detailed monitoring of canopy structure, land conversion, peat subsidence, and vegetation health [53]. Machine-learning models classify land cover with 80–95% accuracy, strengthening the reliability of carbon stock estimations and deforestation detection [54]. When combined with direct field measurements, remote sensing reduces uncertainty in carbon stock calculations by 12–20%, enhancing MRV accuracy [55].

Digital methane sensors installed in digesters and biogas facilities enable real-time measurement of gas composition, pressure, and leakage with error margins of ±5% or less, compared with ±20–30% using traditional estimation methods [56]. Mills adopting digital monitoring systems report 12–18% improvements in methane capture efficiency due to optimized temperature control, pressure management, and early leak detection [57].

A subset of studies illustrates the potential of blockchain-based traceability systems, which reduce the risk of data tampering by 30–40% and support transparent reporting of carbon intensity along the supply chain [58]. Overall, digital MRV enhancements reduce reporting gaps by 10–17%, improving compliance with sustainability standards and strengthening alignment with net-zero objectives [59].

### **Policy and Governance Mechanisms Supporting Decarbonization**

Policy and governance frameworks shape the enabling environment for decarbonization in oil palm plantations. Carbon pricing mechanisms typically simulated in studies at USD 5–20 per ton CO<sub>2</sub>-eq enhance the economic feasibility of methane capture and biomass-based energy projects by 15–40%, depending on regional cost structures and power tariffs [60].

Renewable energy purchase agreements further improve the financial viability of biogas-to-power plants, particularly in countries where grid emission factors exceed 0.7 kg CO<sub>2</sub>/kWh [61]. Sustainability certification systems, most notably RSPO and ISPO, also serve as critical governance tools. RSPO's greenhouse gas module has been shown to reduce plantation emissions by 12–18% through the mandatory implementation of best management practices, including zero-burning policies, peatland protection, and enforcement of riparian buffer zones [62].

The cross-theme synthesis demonstrates that decarbonization in oil palm plantations requires a multidimensional approach in which each strategy contributes a distinct portion of the total mitigation potential identified through the SLR. Methane mitigation offers the largest impact, accounting for approximately 25–35% of the overall emissions reduction potential, primarily due to the substantial methane loads generated by untreated POME. Energy-efficiency improvements and renewable fuel substitution provide an additional 15–25% reduction by lowering fossil fuel dependency and optimizing mill-level energy performance. Ecological interventions through landscape-based carbon sequestration contribute another 8–18%, reflecting the combined effects of biomass accumulation, soil carbon enhancement, and peatland rehabilitation. Digital MRV and monitoring technologies add 10–17% indirectly by improving measurement accuracy, reducing reporting gaps, and enabling better operational control over emission sources. Meanwhile, governance instruments, including certification standards, regulatory frameworks, and carbon-pricing incentives, support 10–20% of overall mitigation by shaping institutional conditions that facilitate technology adoption and compliance. Integrated across all pathways, these strategies collectively indicate that the palm oil sector has the technical and institutional capacity to achieve 55–70% reductions in total emissions, depending on technology uptake, land characteristics, and the strength of policy enforcement.

## Discussion

The purpose of this study was to synthesize peer-reviewed evidence on decarbonization strategies in oil palm plantations and to evaluate their implications for achieving net-zero emissions. Based on an analysis of 39 studies selected for the SLR, the discussion below addresses the two research questions guiding the review. The first examines which strategies offer the highest greenhouse-gas (GHG) reduction potential across plantation and mill operations, while the second evaluates how technological, ecological, and governance pathways differ in terms of implementation feasibility and alignment with long-term climate goals. This section integrates cross-theme interpretations, compares findings across the literature, and identifies implications for future research and policy development.

### Addressing RQ1: Identifying the Most Effective Decarbonization Strategies

The synthesis of studies reveals that methane mitigation from palm oil mill effluent (POME) consistently emerges as the most effective and impactful decarbonization strategy, both in terms of the magnitude of emission reductions and technological maturity. Across the literature, untreated POME is found to contribute between 28–34% of total GHG emissions associated with palm oil production, mainly due to the high methane concentration (65–70% CH<sub>4</sub>) produced during anaerobic decomposition [63]. The installation of covered anaerobic digesters, floating geomembrane systems, or continuous stirred-tank reactors reduces methane emissions by 65–88%, corresponding to 800–1,200 kg CO<sub>2</sub>-eq mitigation per ton of crude palm oil (CPO) [64,65]. These

values position methane capture as the single largest contributor to potential sector-wide decarbonization.

Beyond methane reduction, several studies highlight the importance of biogas-to-energy conversion, which enables mills to replace between 20–30% of purchased electricity with renewable biogas-derived power [66]. In large mills, biogas power generation capacity reaches 3–4.5 MW, significantly reducing grid-related Scope 2 emissions. Considering the high global warming potential (GWP) of methane and the scalability of digesters, methane mitigation is consistently identified as the most immediate and quantifiable pathway toward net-zero operations.

The second-highest contributor to emissions reduction is energy efficiency and renewable fuel substitution, especially within milling operations. Efficiency upgrades such as high-pressure boilers (28–32 bar), steam-trap optimization, and variable-speed motor drives result in energy savings of 10–22%, equivalent to reductions of 120–260 kg CO<sub>2</sub>-eq per ton of CPO [67]. When mesocarp fiber and palm kernel shell (PKS) fully replace industrial diesel oil (IDO), emissions from heat generation fall by 350–500 kg CO<sub>2</sub>-eq per ton of steam produced [68]. Even partial electrification of field transport systems yields 25–45% reductions in diesel-related emissions, especially when charging systems are integrated with biogas-based power [69]. Collectively, these strategies account for 15–25% of the decarbonization potential, making energy efficiency the second-most effective pathway.

The third major strategy involves landscape-based carbon sequestration, which contributes between 8–18% of total mitigation potential. Mature oil palm stands sequester 2.8–7.3 tons CO<sub>2</sub> per hectare per year, although sequestration capacity varies by age and site conditions [70]. Riparian buffer restoration, agroforestry boundary planting, and enhanced groundcover diversity increase carbon stocks in both biomass and soil systems. However, peatland restoration emerges as the most significant ecological intervention. Peatlands emit 40–69 tons CO<sub>2</sub>-eq per hectare per year when drained, dwarfing sequestration potential on mineral soils [71]. Rewetting and water-table stabilization reduce peat oxidation emissions by 20–50%, making peatland management essential to any credible net-zero strategy [72].

The fourth strategy pertains to digital monitoring and MRV (measurement, reporting, and verification) systems. While digital technologies do not directly reduce emissions, they improve verification accuracy and help identify mitigation opportunities. Machine-learning classification of canopy and land-cover changes achieves 80–95% accuracy, reducing uncertainty in carbon stock assessment by 12–20% [73]. IoT-based methane sensors installed on digesters reduce measurement errors to ±5%, compared with ±20–30% under manual estimation methods [74]. MRV enhancements contribute indirectly to decarbonization by reducing reporting gaps, optimizing digester performance, and increasing accountability for emission sources.

Finally, policy and governance frameworks constitute the fifth major decarbonization pathway. Carbon pricing schemes modeled at USD 5–20 per ton CO<sub>2</sub>-eq increase adoption likelihood for methane capture and renewable energy systems by 15–40%, particularly in contexts where electricity tariffs remain high [75]. Sustainability certification programs (e.g., RSPO, ISPO) reinforce adoption of best practices in peatland protection, zero-burning policies, and greenhouse-gas reporting, reducing emissions by 12–18% across compliant plantations [76]. Though governance mechanisms alone do not directly generate emissions

reductions, they shape sector-wide incentives and mitigate barriers to technology deployment.

Synthesizing all evidence, the most effective decarbonization strategies identified in RQ1 can be summarized as follows:

- Methane mitigation: 25–35% emissions reduction
- Energy efficiency & renewable fuels: 15–25%
- Landscape sequestration: 8–18%
- Digital MRV: 10–17% (measurement accuracy gains)
- Governance mechanisms: 10–20% (policy-driven adoption)

Thus, the literature indicates that comprehensive decarbonization requires a combination of high-impact technological interventions and cross-cutting governance measures.

### **Addressing RQ2: Comparing Technological, Ecological, and Governance-Based Pathways**

Research Question 2 focuses on understanding how different categories of decarbonization strategies, technological, ecological, and governance-based, vary in terms of carbon-reduction potential, feasibility of adoption, and compatibility with long-term net-zero transition requirements. The review highlights substantial variation in the scale, stability, and replicability of these pathways.

### **Technological Strategies: Effectiveness, Scalability, and Economic Considerations**

Technological interventions provide the largest and most measurable emission reductions, particularly methane capture and energy-efficiency upgrades. Methane mitigation reduces emissions by 800–1,200 kg CO<sub>2</sub>-eq per ton of CPO, far exceeding the reductions from ecological or governance-based strategies [77]. Moreover, methane capture systems are compatible with energy self-sufficiency goals, reducing operational costs over time. However, capital expenditure for digesters can be substantial, ranging from USD 1–5 million depending on system size, which may limit adoption among small and medium-scale mills.

Energy-efficiency interventions are comparatively easier to implement and often provide faster returns on investment. Installing variable-speed drives, optimizing boiler pressure, or improving steam distribution can yield immediate energy savings without requiring extensive structural overhauls. Despite lower overall mitigation potential than methane capture, efficiency improvements are highly feasible and scalable, making them valuable components of net-zero transition roadmaps.

Digital MRV technologies represent a distinct form of technological intervention. Although they do not directly reduce emissions, they enable high-resolution monitoring, leak detection, and data-driven decision-making, all of which support the effectiveness of mitigation systems. Digital systems also help improve accuracy in compliance reporting, which is increasingly important given emerging global regulations on supply-chain traceability.

### **Ecological Strategies: Long-Term Potential and Landscape Resilience**

Ecological strategies, particularly carbon sequestration and peatland restoration, offer long-term mitigation potential that complements the immediate reductions from technological interventions. While sequestration rates (2.8–7.3 tons CO<sub>2</sub>/ha/year) are relatively modest compared with methane mitigation, their cumulative effect across millions of hectares of plantations is substantial [78]. Riparian restoration, soil carbon enhancement, and agroforestry interventions also contribute co-benefits, including

improved biodiversity, erosion control, and water regulation.

The most significant ecological intervention is the restoration of peatland hydrology. Given that drained peatlands emit 40–69 tons CO<sub>2</sub>-eq/ha/year, restoring water tables can yield reductions comparable to or greater than those from technological strategies [79]. Ecological measures typically have lower technical requirements but involve greater variability in outcomes due to climatic, hydrological, and soil factors.

Ecological strategies help stabilize carbon stocks and ensure long-term sustainability, but they require strong governance, continuous monitoring, and financial support to ensure effectiveness. Compared to technological interventions, ecological strategies are slower to implement and may take years to yield measurable carbon benefits.

### **Governance-Based Pathways: Catalysts for Adoption and Compliance**

Governance-based strategies, including certification standards, carbon-pricing mechanisms, land-use regulations, and renewable energy incentives, serve as enabling frameworks for decarbonization. While they do not directly reduce emissions, they enhance institutional feasibility, financial attractiveness, and regulatory clarity.

Carbon pricing increases the feasibility of investing in methane capture systems, particularly in regions with high electricity costs and weak market incentives [80]. Certification schemes enforce compliance with climate-relevant practices, and international buyers increasingly require evidence of low-carbon production. Governance frameworks also play a key role in regulating peatland conversion, enforcing riparian buffer zones, and establishing MRV requirements.

Compared with technological and ecological strategies, governance mechanisms exhibit the greatest heterogeneity across countries. Effective governance requires alignment among national policies, industry commitments, and global market expectations, which is often challenging given varying regulatory capacities. Nevertheless, governance functions as the backbone that enables technological and ecological interventions to achieve meaningful scale.

### **Cross-Category Comparison and Integration Toward Net-Zero Pathways**

When comparing technological, ecological, and governance strategies, one central insight emerges: no single pathway can achieve net-zero emissions alone. Technological systems deliver the most immediate and quantifiable reductions; ecological strategies stabilize carbon stocks over the long term; and governance mechanisms create an enabling environment for widespread adoption. The literature consistently supports a hybrid decarbonization model that integrates methane capture, renewable fuel substitution, peatland restoration, landscape-based sequestration, digital MRV, and certification systems [81].

High-impact strategies offer strong reduction potential but require stable governance structures to achieve scale. At the same time, ecological approaches deliver long-term resilience and can offset emissions that are difficult to eliminate technologically. In practice, the most successful decarbonization trajectories documented in the literature involve:

- Methane capture + biogas power integration
- High-efficiency boiler systems + biomass substitution

- Peatland rewetting + riparian restoration
- Remote sensing-based MRV + certification compliance
- Incentive-based policy frameworks + private-sector climate commitments

These combined interventions create synergistic outcomes that exceed the mitigation potential of isolated strategies.

The findings of this review highlight several implications for practitioners, policymakers, and researchers. First, methane mitigation technologies should be prioritized as the core component of net-zero strategies in the palm oil sector, given their high emission-reduction potential and strong technological maturity. Second, national and corporate sustainability plans should integrate energy-efficiency upgrades and biomass fuel substitution to complement methane reduction and reduce reliance on fossil fuels. Third, peatland restoration and landscape-based ecological interventions must be scaled to ensure long-term carbon stabilization, particularly in regions dominated by peat soils.

In terms of policy, governments should strengthen carbon-pricing mechanisms, enforce land-use regulations, and expand renewable energy incentives to increase the financial feasibility of decarbonization technologies. Meanwhile, research should further explore hybrid decarbonization models that integrate technological and ecological pathways under different geographic, climatic, and institutional contexts. Future studies may also investigate smallholder inclusion in decarbonization systems, digital MRV cost structures, and long-term monitoring of peatland restoration performance.

Together, these insights reinforce the need for a long-term, multidimensional approach that combines technology, ecological restoration, and governance transformation to achieve net-zero emissions in oil palm plantations.

## Conclusion

This systematic review demonstrates that achieving net-zero emissions in oil palm plantations requires a combination of high-impact technological interventions, long-term ecological strategies, and governance mechanisms that reinforce adoption and compliance. Across the 39 peer-reviewed studies analyzed, methane mitigation from palm oil mill effluent (POME) consistently emerges as the most effective decarbonization strategy due to its substantial reduction potential and technological readiness. Methane capture systems reduce emissions by up to 65–88%, representing the largest and most immediate contribution to lowering the sector's greenhouse-gas footprint. When integrated with biogas-to-energy applications, these interventions further reduce reliance on grid electricity and strengthen the energy autonomy of processing facilities.

Energy-efficiency improvements and renewable fuel substitution constitute the next most impactful mitigation pathway. The adoption of high-pressure boilers, optimized steam systems, and variable-speed drives delivers substantial energy savings in mill operations, while the use of biomass residues, such as palm kernel shell and mesocarp fiber, significantly reduces reliance on fossil fuels. These measures collectively contribute to meaningful reductions in operational emissions and enhance the feasibility of low-carbon production systems.

Ecological strategies provide an essential complement to technological measures by offering long-term carbon stabilization across plantation landscapes. Carbon sequestration in mature palm stands, riparian restoration, and enhanced soil organic carbon

accumulation contribute measurable mitigation benefits. However, peatland restoration stands out as a critical intervention, given that drained peatlands are among the highest-emitting land-use types in the sector. Rewetting and water-table management significantly reduce peat oxidation emissions, underscoring the central role of ecological rehabilitation in any credible net-zero scenario.

Digital monitoring technologies and MRV (measurement, reporting, and verification) systems strengthen transparency and improve emissions accounting across supply chains. Remote sensing, machine learning, and IoT-based methane sensors reduce uncertainty in carbon measurements and enhance the operational efficiency of mitigation technologies. Although these innovations do not directly reduce emissions, they play an increasingly important enabling role by improving accuracy, accountability, and traceability, factors demanded by global markets and regulatory frameworks.

Governance mechanisms, including sustainability certification, carbon-pricing instruments, land-use regulations, and renewable energy incentives, serve as structural enablers of decarbonization. These frameworks improve the economic attractiveness of mitigation technologies, reinforce compliance with climate-relevant practices, and enhance alignment with international sustainability expectations. Effective governance is therefore indispensable for scaling technological and ecological solutions beyond isolated project-level interventions.

In comparing technological, ecological, and governance-based pathways, this review finds that each category offers distinct strengths and limitations. Technological strategies provide the highest and most immediate emissions reductions but often require significant capital investment and technical expertise. Ecological strategies offer long-term mitigation benefits and landscape resilience but are influenced by environmental variability and require continuous monitoring. Governance-based frameworks do not directly reduce emissions but are essential for ensuring adoption, standardization, and long-term alignment with net-zero goals. The evidence strongly supports an integrated decarbonization model that combines technologically driven mitigation, ecological restoration, and robust governance mechanisms to achieve durable and scalable emissions reductions.

Overall, the findings emphasize that achieving net-zero emissions in oil palm plantations cannot be done with a single intervention. A comprehensive approach built on methane mitigation, energy transformation, ecological restoration, digital verification, and supportive governance is required to deliver sustained climate benefits. Future research should further examine hybrid strategies that integrate these pathways across diverse environmental and institutional contexts, assess long-term performance using advanced MRV systems, and explore mechanisms to enable smallholder participation to ensure sector-wide decarbonization.

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