



# Emissions Reduction Technologies in Palm Oil Production: A Review of Decision Frameworks for Climate Action Implementation

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### Abstract

The palm oil industry faces mounting pressure to reduce greenhouse gas emissions while maintaining its crucial role in global food systems and economic development. This systematic literature review examines emissions-reduction technologies available across palm oil production systems and the decision frameworks that guide their implementation for climate action. Following PRISMA guidelines, a comprehensive search of Scopus and Web of Science databases identified 87 peer-reviewed articles published between 2016 and 2025 that address technological interventions, decision-making processes, and determinants of adoption in the palm oil sector. The bibliometric analysis reveals exponential growth in research attention, with publication peaks in 2023-2024 coinciding with heightened climate commitments and certification requirements. Thematic analysis identifies five major technology categories demonstrating significant mitigation potential: biogas capture from palm oil mill effluent achieving 65-90% methane reduction, renewable energy integration through biomass utilization reducing fossil fuel dependence by 80-90%, precision agriculture optimizing fertilizer application and reducing nitrous oxide emissions by 20-35%, agroforestry systems increasing ecosystem carbon stocks by 20-40%, and emerging technologies including pyrolysis and advanced wastewater treatment. However, the review reveals a critical gap between the availability of decision frameworks and their practical application, with Multi-Criteria Decision Analysis, Life Cycle Assessment, and Technology Readiness Level assessments rarely integrated into industry decision-making. Barriers to technology adoption differ substantially across stakeholder types, with smallholders experiencing compounded constraints including high capital costs, limited access to finance, exclusion from certification schemes, and inadequate technical support. Institutional factors, including RSPO certification, national policies, and governance structures, profoundly shape adoption dynamics but face implementation challenges related to enforcement, bureaucratic complexity, and inadequate financing mechanisms. The findings underscore the need for integrated approaches that combine technological innovation with tailored decision-support tools, differentiated stakeholder interventions, and strengthened institutional frameworks to accelerate climate action in the palm oil sector.

**JEL Classification Codes :** Q55; Q54; Q16; Q18; Q13

### Introduction

### Background

The palm oil industry occupies a paradoxical position in contemporary sustainability discourse, simultaneously representing one of the most efficient vegetable oil production



systems and one of the most scrutinized agricultural commodities for its environmental impacts. As the world's most widely consumed vegetable oil, palm oil accounts for approximately one-third of global vegetable oil production while occupying only 6% of the land dedicated to oil-crop cultivation, demonstrating remarkable land-use efficiency compared with alternative oilseeds such as soybean, rapeseed, and sunflower. Indonesia and Malaysia collectively account for approximately 85% of global palm oil production, with the industry supporting millions of livelihoods and contributing significantly to national export revenues and rural economic development. However, this economic significance is accompanied by substantial environmental concerns, particularly regarding greenhouse gas emissions from land use changes, peatland degradation, and production processes that contribute to climate change [1,2].

The carbon footprint of palm oil production varies considerably depending on management practices, ranging from 600 to 1,500 kg CO<sub>2</sub>-equivalent per ton of crude palm oil when land-use change impacts are excluded. Palm Oil Mill Effluent (POME) is the largest single point source of methane emissions in production operations, with untreated effluent releasing approximately 0.38 kg of methane per cubic meter through anaerobic decomposition. Given that methane has a global warming potential 25-28 times that of carbon dioxide over a 100-year horizon, POME management emerges as a critical intervention for emissions mitigation. Additionally, agricultural practices, including fertilizer application, contribute to nitrous oxide emissions, a particularly potent greenhouse gas with a warming potential 298 times that of carbon dioxide. The collective impact of these emission sources positions the palm oil sector as both a significant contributor to agricultural emissions and a sector with substantial mitigation potential through technological intervention [3,4].

Recent technological developments have demonstrated the feasibility of dramatic emissions reductions across palm oil production systems. Biogas capture systems utilizing anaerobic digestion can recover 65-90% of methane from POME while generating renewable energy for mill operations. Biomass conversion technologies enable palm oil mills to achieve energy self-sufficiency by combusting empty fruit bunches, fiber, and shells, thereby displacing fossil fuel consumption. Precision agriculture approaches optimize fertilizer application, reducing nitrogen inputs by 20-35% while maintaining or improving yields. Agroforestry systems integrating timber or fruit trees within oil palm plantations enhance carbon sequestration and provide biodiversity co-benefits. Despite this technological portfolio, adoption remains fragmented across the industry, with significant disparities between large integrated operations and independent smallholders who produce approximately 40% of global palm oil [5,6].

### Urgency of the Study

The urgency for systematic evaluation of emissions-reduction technologies and decision frameworks stems from converging pressures across multiple scales. At the international level, the Paris Agreement and subsequent Conference of the Parties decisions mandate substantial reductions in agricultural emissions to limit global warming to 1.5°C, with food systems contributing approximately one-third of global greenhouse gas emissions. Major palm oil importing markets, particularly the European Union, are implementing increasingly stringent sustainability requirements through regulations such as the EU Deforestation Regulation, which could restrict market access for producers unable to demonstrate compliance with environmental standards. Financial institutions and investors increasingly demand alignment with environmental, social, and governance criteria, making sustainability performance a determinant of access to capital and insurance. These external pressures create both compliance imperatives and market incentives for emissions reduction [2-7].

At the national level, Indonesia and Malaysia have established ambitious climate commitments through their Nationally Determined Contributions and net-zero emissions targets. Indonesia's target of achieving net-zero emissions by 2060 necessitates transformation across all economic sectors, including agriculture, which accounts for a significant share of national emissions. The palm oil industry's ability to demonstrate emissions reductions is therefore critical to achieving national climate objectives while maintaining the sector's economic contributions. Malaysia's implementation of mandatory Malaysian Sustainable Palm Oil certification represents an effort to institutionalize sustainability practices, though implementation challenges persist, particularly regarding smallholder inclusion. These national policy frameworks create regulatory drivers for technology adoption while also revealing governance gaps that impede progress [8,9].

Despite technological availability, significant implementation gaps persist that warrant systematic investigation. The gap between certified sustainable production, with approximately 20% of global palm oil RSPO-certified, and total output highlights the challenge of scaling emissions reduction technologies. Research examining the decision processes underlying technology selection and adoption remains limited, creating uncertainty about how to accelerate diffusion. Barriers, including high investment costs, limited access to finance, inadequate technical capacity, and weak institutional support, disproportionately affect smallholders, raising equity concerns in sustainability transitions. Understanding how decision frameworks can address these barriers while enabling efficient resource allocation is essential for



designing effective interventions that accelerate climate action across the diverse landscape of palm oil producers [10,11].

## Research Objectives

This systematic literature review aims to comprehensively identify, analyze, and synthesize existing research on emissions-reduction technologies in palm oil production, with specific attention to decision frameworks that facilitate or constrain their implementation for climate action. The primary objective is to map the current state of knowledge on technological interventions and decision-making processes, and to identify research gaps warranting future investigation. The review pursues five secondary objectives that collectively address the technology-decision nexus in palm oil climate mitigation.

The first secondary objective is to systematically catalog available emissions-reduction technologies across the palm oil value chain, including plantation-level interventions, mill-level processes, and supply chain practices, and to evaluate their demonstrated mitigation potential and technology readiness levels. The second objective is to identify and critically analyze decision frameworks, including Multi-Criteria Decision Analysis, cost-benefit analysis, Life Cycle Assessment, and Technology Readiness Level assessment, that guide technology selection and prioritization within the sector. The third objective is to examine barriers and enablers of technology adoption, with particular attention to how these factors differ across stakeholder types, including large plantations, independent mills, and smallholder farmers. The fourth objective is to assess the role of institutional factors, including certification schemes, policy instruments, and governance structures, in shaping technology adoption decisions and outcomes. The fifth objective is to identify critical research gaps and propose future research directions to accelerate climate action in the palm oil sector [12].

## Research Questions

This systematic review is guided by five research questions that structure the analysis and synthesis of literature. The first research question asks which primary emissions-reduction technologies are available for palm oil production across plantation, milling, and supply chain operations, and what their demonstrated mitigation potential is. This question addresses the technological landscape and provides the foundation for understanding intervention options. The second research question investigates which decision frameworks, both theoretical and applied, are employed or proposed in the literature to guide the selection and implementation of emissions-reduction technologies in the palm oil sector. This question examines the decision-making dimension that mediates between technological availability and actual adoption [13].

The third research question explores the key barriers and enablers influencing the adoption of emissions-reduction technologies and how these factors differ across stakeholder types, including large-scale plantations, palm oil mills, and independent smallholders. Understanding stakeholder-differentiated constraints is essential for designing targeted interventions that address specific needs. The fourth research question examines how institutional factors, including certification schemes, policy frameworks, and governance structures, influence technology adoption decisions and implementation outcomes. Institutional analysis provides insight into the broader context shaping technology diffusion. The fifth research question asks what critical research gaps exist in understanding decision-making processes for climate technology implementation in the palm oil sector, and what future research directions would most effectively advance climate action. This forward-looking question aims to guide future scholarship toward areas of greatest need and potential impact [14].

## Literature Review: Theoretical Frameworks

### Technology Diffusion and Adoption Theories

The adoption of emissions-reduction technologies in agricultural systems is fundamentally shaped by innovation-diffusion processes that determine how technological innovations spread through social systems over time. Rogers' Diffusion of Innovations theory provides a foundational framework for understanding adoption dynamics, positing that innovation diffusion follows an S-curve pattern characterized by initially slow adoption among innovators, acceleration through early adopters and early majority, and eventual saturation as late majority and laggards adopt. The theory identifies five characteristics of innovations that influence adoption rates: relative advantage over existing practices, compatibility with adopters' values and needs, complexity of understanding and use, trialability that enables experimentation, and observability that allows potential adopters to witness results. In the context of palm oil emissions reduction, relative advantage encompasses both environmental benefits and economic returns, such as energy cost savings from biogas utilization. At the same time, compatibility relates to fit with existing operational practices and infrastructure [15].

The Technology-Organization-Environment framework complements diffusion theory by examining three contextual dimensions that shape organizational decisions about technology adoption. The technological dimension encompasses characteristics such as perceived benefits, complexity, and compatibility with existing systems that influence the feasibility and attractiveness of adoption. The organizational dimension addresses internal factors, such as organizational size, management support, technical capacity, and resource

availability, that determine an organization's capability to adopt. The environmental dimension captures external pressures, including competitive dynamics, regulatory requirements, and industry norms that create incentives for or constraints on adoption. For palm oil producers, environmental factors, including certification requirements and buyer sustainability demands, increasingly drive technology adoption, while organizational factors, such as access to capital and technical expertise, determine implementation capacity [16].

The technology adoption lifecycle further refines understanding by categorizing adopters based on the timing of their adoption and their risk tolerance. Innovators represent the first 2.5% of adopters, characterized by venturesome risk-taking and access to resources enabling experimentation with unproven technologies. Early adopters comprise approximately 13.5% of the population and serve as opinion leaders whose adoption decisions influence subsequent diffusion. The early majority represents 34% of adopters who deliberate before adoption, while the late majority, similarly, represents 34% of adopters who adopt primarily due to social pressure or necessity. Laggards, comprising the final 16% resist change and adopt only when alternatives become unavailable. In the palm oil sector, large integrated companies with research capacity and access to capital typically occupy innovator and early adopter positions. At the same time, smallholders predominantly fall into the late majority and laggard categories due to resource constraints and risk aversion [17-19].

### **Institutional Theory and Sustainability Transitions**

Institutional theory provides critical insights into how formal and informal institutions shape organizational behavior toward sustainability practices and technology adoption. New institutional theory distinguishes three institutional pillars that collectively influence organizational conduct: the regulatory pillar encompassing formal rules, laws, and sanctions enforced by governmental authorities; the normative pillar comprising professional standards, industry best practices, and social obligations that define appropriate behavior; and the cultural-cognitive pillar reflecting taken-for-granted beliefs, shared understandings, and established routines that shape perception and action. In the palm oil sector, the regulatory pillar includes mandatory certification requirements, such as ISPO in Indonesia and MSPO in Malaysia; environmental regulations governing emissions and waste management; and land-use policies restricting development on peatlands and forests [20].

The normative pillar encompasses voluntary certification schemes such as RSPO that establish industry standards for sustainable production, buyer sustainability requirements transmitted

through supply chains, and professional norms regarding environmental responsibility. The cultural-cognitive pillar reflects deeply embedded beliefs about agricultural practices, land use, and development trajectories that shape producers' perceptions of sustainability interventions. Institutional theory suggests that organizations adopt practices not solely based on efficiency calculations but also to gain legitimacy by conforming to institutional expectations, a phenomenon termed institutional isomorphism. Coercive isomorphism results from formal pressures, including regulations and contractual requirements; mimetic isomorphism occurs when organizations imitate successful peers under uncertainty, and normative isomorphism derives from professionalization and shared training that diffuse common practices [21-24].

Institutional logics theory extends this analysis by examining how competing rationalities create tensions and opportunities within organizational fields. In palm oil sustainability, multiple logics operate simultaneously: a market logic emphasizing profitability, efficiency, and competitiveness; a state logic focusing on regulatory compliance, food security, and national development; and a sustainability logic prioritizing environmental protection, social responsibility, and long-term ecosystem health. Organizations navigating between these logics must balance potentially conflicting demands, and technology adoption decisions often reflect this negotiation. For example, biogas capture technology becomes attractive when it simultaneously generates economic returns that satisfy market logic, meets regulatory requirements that address state logic, and reduces emissions that align with sustainability logic. Conversely, when logics conflict, such as when sustainability investments reduce short-term profitability, adoption may be delayed until institutional pressures sufficiently shift the balance [2,25].

### **Decision Analysis and Technology Assessment Frameworks**

Multi-Criteria Decision Analysis methods provide structured approaches for evaluating technology alternatives under multiple, often conflicting, criteria that characterize complex sustainability decisions. These methods systematically integrate diverse evaluation dimensions, enabling decision-makers to compare alternatives across technical, economic, environmental, and social considerations. The Analytic Hierarchy Process represents one of the most widely applied MCDA methods in energy and environmental contexts, utilizing hierarchical structuring of decision problems and pairwise comparisons to derive priority weights for criteria and alternatives. Studies applying AHP to renewable energy selection demonstrate its utility for balancing competing objectives while providing transparent justification for technology choices [26].

The Technique for Order Preference by Similarity to Ideal Solution ranks alternatives based on their distances from ideal and anti-ideal solutions, identifying options that minimize distance from the best possible performance while maximizing distance from the worst possible performance. VIKOR and COPRAS methods similarly provide compromise ranking approaches that balance group utility and individual regret in multi-stakeholder contexts. The selection of MCDA methods influences results, as different techniques make different assumptions about criterion independence, criterion compensation, and the treatment of uncertainty. Hybrid approaches that combine multiple methods or integrate subjective expert judgments with objective data-driven analysis offer enhanced robustness in complex decisions [27].

Life Cycle Assessment provides a comprehensive environmental evaluation by quantifying emissions and impacts across entire value chains from raw material extraction through production, use, and disposal. LCA studies in palm oil have established emissions baselines, identified hotspots requiring intervention, and compared technology scenarios. Methodological choices significantly influence results, including system boundary definitions that determine which processes are included, functional unit selection that enables comparison across products, and allocation methods that distribute impacts among co-products. The RSPO PalmGHG calculator is an effort to standardize greenhouse gas accounting in the sector, enabling comparisons across producers and supporting decision-making. However, methodological complexity, data requirements, and variability in results have limited LCA integration into routine industry decision-making [28].

Technology Readiness Level assessment frameworks evaluate innovation maturity along a spectrum from basic research through commercial deployment. The nine-level TRL scale, originally developed by NASA and subsequently adopted across sectors, provides standardized terminology for communicating technology status to investors, policymakers, and adopters. In the palm oil sector, TRL assessment reveals that the highest-impact technologies, including biogas capture and biomass combustion, are commercially mature at TRL 9. In contrast, emerging technologies such as pyrolysis and advanced wastewater treatment are in the pilot-to-demonstration stages at TRL 5-7. TRL assessment informs investment decisions by identifying technologies ready for deployment versus those requiring further development support, and guides portfolio approaches that balance near-term implementation with long-term innovation [29].

## Climate Policy and Governance Frameworks

Effective technology transfer and adoption require supportive policy frameworks operating at multiple scales, from international agreements through national strategies to local implementation mechanisms. The United Nations Framework Convention on Climate Change Technology Mechanism, comprising the Technology Executive Committee and the Climate Technology Centre and Network, provides an international architecture for facilitating the development and transfer of climate technology to developing countries. These mechanisms support technology needs assessments, capacity building, and access to financing, though palm oil-specific interventions remain limited. At the national level, climate change framework laws and strategies establish institutional mandates, coordination mechanisms, and accountability structures for implementing Nationally Determined Contributions [30].

For Indonesia and Malaysia, commitments in the palm oil sector intersect with broader national climate targets, requiring integrated policy approaches that address sectoral emissions while maintaining economic contributions. Key policy instruments operating within these frameworks include regulatory mandates, such as certification requirements and environmental standards; financial incentives, including carbon pricing mechanisms and renewable energy tariffs; and support programs encompassing extension services, research funding, and financing facilitation. Malaysia's feed-in tariff for biogas-generated renewable electricity has significantly improved the technology's economics, accelerating adoption compared to jurisdictions without such incentives. Indonesia's carbon trading framework is an emerging market mechanism that could support emissions-reduction investments if implementation challenges are addressed [31-33].

Technology transfer frameworks distinguish between "hard" transfer, involving physical equipment and infrastructure, and "soft" transfer, encompassing knowledge, skills, and institutional capacity. Effective technology deployment requires attention to both dimensions, as equipment installation without corresponding operational capacity leads to underperformance or abandonment. Financial mechanisms, including concessional lending, green bonds, and carbon credit pre-financing, can address capital constraints, while technical assistance, training programs, and peer learning networks build absorptive capacity. The design of policy portfolios combining regulatory push with economic pull while addressing capacity gaps represents a critical challenge for accelerating technology diffusion across diverse producer types with varying needs and capabilities [34].

## Methodology

### Systematic Literature Review Approach

This study employs a Systematic Literature Review methodology, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines, to ensure a rigorous, transparent, and replicable synthesis of scientific evidence. The PRISMA 2020 statement provides a 27-item checklist and flow diagram that structures the review process from search strategy through screening, eligibility assessment, and synthesis. Systematic reviews differ from traditional narrative reviews in that they use explicit, pre-specified protocols that minimize selection bias and enhance reproducibility, enabling readers to assess review quality and replicate findings. The methodology is particularly appropriate for this research, as it enables comprehensive mapping of a rapidly evolving, multidisciplinary research domain while systematically identifying knowledge gaps and synthesizing diverse types of evidence [35].

The SLR approach addresses the research questions through sequential phases of identification, screening, eligibility assessment, and inclusion that progressively refine the literature corpus to include only studies that meet quality and relevance criteria. Following the PRISMA 2020 update, the methodology emphasizes transparent reporting of search strategies, explicit documentation of screening and eligibility decisions, and comprehensive presentation of synthesis methods. The review integrates both bibliometric analysis, which provides a quantitative characterization of the research landscape, and thematic analysis, which enables a qualitative interpretation of findings across technology, decision framework, and implementation dimensions [36, 37].

### Search Strategy and Information Sources

The literature search was conducted across multiple reputable databases to ensure comprehensive coverage of relevant publications spanning engineering, environmental science, agricultural economics, and policy studies. Scopus served as the primary database due to its extensive coverage of peer-reviewed journals, systematic indexing, and advanced search capabilities, which enabled precise query formulation. Web of Science Core Collection provided complementary coverage of high-impact scientific literature. At the same time, Google Scholar was used to supplement the search to identify potentially relevant grey literature and working papers not captured in subscription databases [35].

The search strategy employed Boolean logic combining three concept groups representing the core elements of the research

focus. The first concept group addressed technological interventions using terms including "emission\* reduction" OR "greenhouse gas mitigation" OR "GHG mitigation" OR "climate mitigation" OR "biogas" OR "methane capture" OR "renewable energy" OR "precision agriculture" OR "agroforestry" OR "biomass utilization" OR "carbon sequestration". The second concept group specified the sectoral context using terms including "palm oil" OR "oil palm" OR "palm plantation\*" OR "palm oil mill" OR "POME" OR "crude palm oil". The third concept group captured the decision and implementation dimension using terms including "decision framework\*" OR "technology adoption" OR "implementation" OR "multi-criteria" OR "MCDA" OR "cost-benefit analysis" OR "policy framework\*" OR "certification" OR "RSPO" OR "ISPO" [36].

The search was limited to articles published between January 2016 and March 2026 to ensure contemporary relevance while capturing the substantial growth in research attention following the Paris Agreement and strengthened certification requirements. Language restrictions limited inclusion to English-language and Bahasa Indonesia/Malaysia publications to ensure analytical consistency. The search was conducted during March 2026, with results exported to a reference management software for deduplication and systematic screening.

### Inclusion and Exclusion Criteria

Explicit inclusion and exclusion criteria structured the screening process to identify studies directly relevant to the research questions while maintaining methodological quality standards. Inclusion criteria specified that studies must be peer-reviewed journal articles indexed in Scopus or Web of Science to ensure quality and rigor, and must address emissions reduction technologies in palm oil production systems, including plantations, mills, or supply chains. Studies were included if they examined decision-making processes, frameworks, or factors influencing technology adoption, or evaluated policy frameworks, certification schemes, or governance mechanisms related to emissions reduction. Research that provided empirical data, case studies, or theoretical frameworks relevant to the research questions was included, along with studies demonstrating methodological rigor appropriate to their research designs [35].

Exclusion criteria removed review articles, book chapters, conference proceedings, and grey literature from the primary corpus while allowing their use as supplementary sources for contextual information. Studies focusing solely on land-use change or deforestation, without addressing production-related emissions and technologies, were excluded to maintain focus on the specific research scope. Articles examining palm oil

sustainability broadly, without specific attention to emissions reduction technologies or decision frameworks, were excluded, as were studies focused exclusively on other oil crops without comparative analysis, including palm oil. Opinion pieces, editorials, and commentaries lacking empirical evidence or rigorous methodology were excluded, along with duplicate publications and articles without full-text access. Studies published before 2016 were excluded to ensure contemporary relevance, given rapid technological and policy developments in the intervening period [36].

### Study Selection Process

The study selection followed the PRISMA four-stage process, documented in a flow diagram that tracked article progression from identification to final inclusion. The identification stage encompassed database searching and duplicate removal. Initial database searches yielded a combined total of 847 records from Scopus, Web of Science, and supplementary sources. Following automated and manual deduplication using reference management software, 612 unique records remained for screening.

The screening stage involved reviewing titles and abstracts against the inclusion criteria. Two researchers independently screened all unique records using a standardized checklist, with disagreements resolved through discussion and reference to eligibility criteria. Records clearly outside the research scope were excluded with reasons documented. Following title and abstract screening, 156 records were retained for full-text eligibility assessment. The eligibility stage involved a detailed full-text review of retained records against inclusion and exclusion criteria. Full texts were retrieved and independently assessed by two reviewers, with exclusion reasons documented for transparency. The reference lists of included studies were screened to identify additional relevant articles, and forward citation searching identified recently published studies that cited foundational works. Following full-text assessment, 87 studies met all eligibility criteria and were included in the final synthesis.

### Data Extraction and Quality Assessment

A standardized data extraction form captured relevant information from included studies across multiple dimensions. Bibliographic information encompassed authors, publication year, journal name, DOI, and citation count. Study characteristics included research design, geographic focus, time period covered, and data sources. Technology focus documented: specific emissions-reduction technologies examined, value chain segment addressed, and technology readiness level assessed. Decision framework elements captured include the analytical approaches employed, the evaluation criteria utilized, the stakeholders

involved, and the methods applied. Key findings documented emissions-reduction potential, adoption rates, identified barriers and enablers, and offered policy recommendations. Quality indicators assessed sample size adequacy, methodological rigor, data quality, and acknowledgment of limitations [38, 39].

Study quality was assessed using criteria appropriate for diverse research designs represented in the corpus. In empirical studies, quality assessment examined the clarity of research questions, the appropriateness of the methodology, the representativeness of the sample, the rigor of data collection, and the statistical appropriateness. For modeling and assessment studies, the evaluation addressed model-structure transparency, data quality and sources, validation procedures, and the generalizability of the findings. For case studies, the assessment considered the completeness of the context description, data triangulation, analytical depth, and transferability. Quality assessment informed the synthesis process, enabling consideration of how study quality relates to findings while avoiding exclusion based solely on quality scores, given the diverse methodological landscape [40].

### Data Analysis and Synthesis

Data analysis integrated bibliometric and thematic approaches to comprehensively address the research questions. Bibliometric analysis utilized VOSviewer software to construct and visualize co-authorship networks, co-citation patterns, and keyword co-occurrence relationships, revealing the intellectual structure of the research field. Publication trends, geographic distribution, disciplinary coverage, and citation patterns were analyzed to characterize the research landscape and identify influential works and emerging themes. Network analysis revealed research clusters and collaboration patterns, informing understanding of how knowledge is produced and disseminated within the field [41].

Thematic analysis followed established procedures for qualitative synthesis, involving iterative reading of included studies, identification of recurring concepts and patterns, development of thematic categories, and integration of findings within and across themes. The six-phase thematic analysis process encompassed familiarization with the data through repeated reading; generation of initial codes capturing key features; searching for themes by collating codes into broader patterns; reviewing themes against coded extracts and the full dataset; defining and naming themes; and producing the final synthesis. Themes were organized around the research questions to address the technology landscape, decision frameworks, barriers and enablers, institutional influences, and research gaps. The synthesis narrative integrated findings from bibliometric and thematic analysis to provide a comprehensive and coherent account of the current state of knowledge and directions for future research [37-42].

## Results

### Bibliometric Analysis of Selected Literature

The bibliometric analysis reveals substantial growth in research attention to emissions reduction technologies in palm oil production over the study period, reflecting both increasing recognition of the sector's climate significance and intensifying pressure for sustainable production. Temporal distribution of publications demonstrates three distinct phases: an emergence phase from 2016-2018 characterized by foundational research establishing baseline emissions profiles and initial technology assessments; an acceleration phase from 2019-2021 marked by increased output coinciding with strengthened RSPO requirements and national policy developments; and a maturation phase from 2022-2025 featuring methodological sophistication and integration of technological, economic, and policy dimensions. Publication peaks occurred in 2023-2024, potentially driven by preparations for major climate negotiations, implementation deadlines for sustainability commitments, and technological maturation enabling more comprehensive assessments [43].

The geographic distribution of research aligns with palm oil production geography, with Malaysia contributing approximately 40-45% of publications, reflecting its advanced research infrastructure and proactive MSPO certification system. Indonesia follows, accounting for 30-35% of publications, with contributions proliferating, particularly in studies examining smallholder inclusion and jurisdictional approaches. International collaborative research accounts for approximately 20-25% of publications, featuring partnerships between Southeast Asian institutions and universities in Europe, Australia, and North America, bringing complementary expertise in Life Cycle Assessment, policy analysis, and sustainability science. Emerging contributions from Nigeria, Colombia, and Central African countries signal growing research attention to palm oil sustainability beyond traditional producing regions [44].

The journal and disciplinary distribution reflect the multifaceted nature of emissions-reduction challenges spanning environmental science, agricultural engineering, energy systems, and policy studies. The Journal of Cleaner Production emerges as the most prolific outlet, accounting for approximately 15-20% of included studies, consistent with its focus on cleaner production and industrial ecology. Environmental science and sustainability journals account for approximately 40% of publications; agricultural engineering and technology journals, 25%; energy and renewable resources journals, 20%; and policy and development journals, 15%. This disciplinary spread indicates recognition that emissions reduction in palm oil production requires integrated

approaches spanning technological innovation, economic assessment, and governance reform [24,45].

Network analysis using VO Sviewer reveals prominent research clusters and collaboration patterns. A technology assessment cluster centers on researchers conducting LCA studies and environmental impact assessments, with strong connections to universities in Malaysia and European LCA centers. A biogas and renewable energy cluster focuses on POME treatment, biogas production, and energy recovery, featuring contributions from palm oil research institutes and energy engineering departments. A policy and certification cluster examines the effectiveness of RSPO, ISPO, and MSPO, as well as governance frameworks, and connects universities, NGOs, and international organizations. A smallholder adoption cluster investigates barriers to technology adoption, certification challenges, and socio-economic impacts, linking development studies scholars with agricultural economists. These clusters show moderate interconnection, suggesting opportunities for enhanced integration between technological, policy, and social research streams [39,46,47,48].

### Thematic Analysis: Emissions Reduction Technologies

#### Biogas Capture and Methane Mitigation from POME

Palm Oil Mill Effluent is the largest single point source of methane emissions in palm oil production, making POME treatment a critical intervention for climate mitigation. Untreated POME releases approximately 0.38 kg of methane per cubic meter through anaerobic decomposition in conventional open lagoon systems, contributing significantly to the industry's carbon footprint, given that methane has 25-28 times greater global warming potential than carbon dioxide. The literature consistently identifies POME management as the highest-priority technological intervention, with studies reporting that 53% of CO<sub>2</sub>-equivalent emissions from palm oil production stem from POME [49,50].

Anaerobic digestion systems capture methane from POME using covered lagoons or closed tank reactors, producing biogas that typically contains 55-65% methane and 30-40% carbon dioxide. Advanced systems couple biogas capture with combined heat and power generation, enabling mills to use captured methane to generate electricity that displaces fossil fuel consumption. Studies report that closed anaerobic digester tanks perform better than covered pond systems due to better operational control and shorter retention times for organic degradation. Biogas yields of 0.28-0.34 Nm<sup>3</sup> CH<sub>4</sub> per kg COD removed support electricity generation potentials exceeding 1 GW nationwide in Indonesia alone [51,52].



The emissions-reduction potential of biogas capture is substantial and well documented in the literature. Studies consistently report a 65-90% reduction in methane emissions from POME treatment via biogas systems, translating into system-level decreases of 0.5-1.0 tons CO<sub>2</sub>-equivalent per ton of crude palm oil produced. United Plantations' longitudinal LCA studies demonstrate that methane from POME treatment, previously one of the main contributors to GHG emissions, has been almost eliminated through the installation of digester tanks, replacing anaerobic ponds. At industry scale, universal biogas capture across Malaysian palm oil mills could reduce annual emissions by approximately 4.5 million tons CO<sub>2</sub>-equivalent, representing a significant contribution to national climate targets [53,54].

Despite commercial maturity at TRL 9, biogas capture adoption rates remain below 50% across total mills, with significant variation by producer type. Approximately 70% of large integrated mills have implemented biogas systems, while only 20-30% of independent mills have adopted the technology, reflecting differences in access to capital, technical expertise, and policy incentives. Economic barriers include high capital costs ranging from USD 1-3 million per installation, depending on mill capacity, and extended payback periods without policy support. Malaysian policies mandating biogas capture for new mills and providing feed-in tariffs for renewable electricity have significantly accelerated adoption compared to Indonesia, where such incentives are less developed [25,39,52].

### Renewable Energy Integration through Biomass Utilization

Palm oil mills generate substantial biomass residues that offer significant potential for renewable energy production and fossil fuel displacement. Processing one ton of fresh fruit bunches yields approximately 22-23% empty fruit bunches, 12-14% mesocarp fiber, and 5-6% palm kernel shells, collectively representing 10-15 tons of dry biomass per ton of crude palm oil produced. Currently, fiber and shells are predominantly used as boiler fuel in mills, while empty fruit bunches remain underutilized, with approximately 30-40% returned to plantations as mulch without energy recovery [47,55].

Multiple technological pathways enable biomass conversion to energy, with varying levels of maturity and application contexts. Direct combustion in biomass boilers represents the most mature pathway, converting solid biomass into steam for processing operations and electricity generation. Palm oil mills can achieve energy self-sufficiency through efficient biomass combustion systems, eliminating dependence on diesel generators or grid electricity. Biomass briquetting and pelletization technologies densify residues to improve transportation efficiency and enable

access to the alternative fuel market, with potential applications in co-firing with coal or in dedicated biomass power plants. Advanced thermochemical conversion pathways, including pyrolysis and gasification, transform biomass into bio-oil, syngas, and biochar, though these remain at pilot-to-demonstration scale with TRL 6-7 [56].

The literature documents substantial potential for emissions reductions from comprehensive biomass utilization. Hybrid renewable energy systems combining biomass combustion with solar photovoltaic integration can reduce fossil fuel dependence by 80-90% in palm oil mill operations. Full utilization of palm oil biomass for energy could offset approximately 2-3 million tons of coal equivalent annually in Malaysia, making a significant contribution to national renewable energy targets. Studies report that using empty fruit bunches and POME for biogas yields the greatest absolute reduction in greenhouse gas emissions compared with alternative utilization pathways. The potential electrical energy generation from palm oil mill biomass in Indonesia reaches 4,336 MW, representing a substantial renewable resource [57,58].

Adoption of biomass energy systems varies significantly across producer types: large integrated operations achieve widespread implementation, whereas independent mills and smallholder operations face persistent barriers. Technical barriers include the high moisture content of empty fruit bunches (60-65%), which requires pre-drying for efficient combustion; low energy density, increasing transportation costs from remote mills; and the complexity of advanced conversion technologies, which require specialized expertise. Economic barriers encompass capital investment requirements, competition with alternative biomass uses, such as soil amendment, and limited grid connectivity in rural areas, which constrain the ability to export excess electricity. Enabling factors for successful adoption include policy incentives, such as renewable energy tariffs, access to carbon credits, and integration into corporate sustainability strategies [47,58].

### Precision Agriculture and Input Optimization

Precision agriculture applies information technology, remote sensing, and data analytics to optimize agricultural inputs, offering potential to reduce emissions through improved fertilizer management and enhanced resource efficiency. Conventional fertilization practices in oil palm plantations often result in the over-application of nitrogen fertilizers, contributing to nitrous oxide emissions, a particularly potent greenhouse gas with 298 times the warming potential of carbon dioxide. Precision approaches enable site-specific fertilizer application based on soil nutrient mapping, yield variability, and individual plant requirements, reducing aggregate nitrogen inputs while maintaining or improving yields [60,61].

The technology components enabling precision agriculture in oil palm include multiple sensing and decision-support systems. Remote sensing and satellite imagery monitor plantation health and nutrient status using vegetation indices that detect variability across management units. Drone technology provides high-resolution imaging, enabling individual tree assessment for disease detection and precision application of inputs. Internet of Things sensors deployed within plantations enable real-time monitoring of soil moisture, nutrients, and microclimate conditions. Artificial intelligence-based decision support systems integrate sensor data with agronomic models to generate site-specific recommendations for fertilizer application, irrigation scheduling, and pest management. Variable rate technology enables machinery to automatically adjust input application rates based on spatial variability maps, ensuring appropriate quantities reach each location [61,62].

Studies document meaningful reductions in emissions from the implementation of precision agriculture. Variable-rate fertilizer application technologies have demonstrated reductions of 20-35% in nitrogen fertilizer use, thereby directly lowering nitrous oxide emissions from denitrification processes. Such precision interventions have improved fertilizer use efficiency from an average of 40% under conventional practices to nearly 70%, resulting in yield increases of 8-12% while reducing input costs. Multi-objective lifecycle optimization approaches integrating economic, environmental, and health criteria have identified fertilizer formulations that operate under a CO<sub>2</sub> credit mode, indicating a net reduction in ecological burden across oil palm operations. System-level emissions reductions of 10-15% are achievable for plantation operations implementing comprehensive precision agriculture approaches [4,63,64].

Adoption disparities represent a defining characteristic of precision agriculture in palm oil, with stark contrasts between large plantations and smallholder operations. Large plantations exceeding 10,000 hectares operated by publicly listed companies show adoption rates of 40-60%, driven by access to capital, technical capacity, and data infrastructure. Mid-sized plantations ranging from 1,000-10,000 hectares show emerging adoption at 10-20%, while smallholder adoption remains below 5%. High initial investment costs of USD 100-300 per hectare for complete systems represent the primary barrier, alongside limited digital literacy among farmers, inadequate rural internet connectivity, complexity of data interpretation, and shortage of trained service providers. Successful adoption cases feature cooperative-based implementation models, subsidized access to technology, comprehensive training programs, and ongoing technical support that address multiple barriers simultaneously [61].

## Agroforestry and Carbon Sequestration

Oil palm agroforestry integrates timber trees, fruit trees, or other perennial species into palm plantations, offering pathways for carbon sequestration while potentially enhancing biodiversity and diversifying income. The approach recognizes that oil palm monocultures, while efficient for oil production, may offer limited carbon storage and ecosystem services compared to more diverse production systems. Agroforestry systems aim to capture atmospheric carbon through additional tree biomass while maintaining commercial palm oil production, though design considerations must balance carbon benefits against potential yield competition [6,65,66,67].

Research documents multiple agroforestry system designs with varying configurations and performance characteristics. Alley cropping systems establish alternating rows of oil palms and companion trees, often nitrogen-fixing species that provide fertility benefits and store carbon. Multi-story systems combine oil palm with shade-tolerant understory species, such as coffee, cocoa, or turmeric, that generate additional income while enhancing vegetation complexity. Boundary planting positions trees along plantation borders and waterways, providing carbon storage and ecological connectivity without competing with oil palm production within main plantation blocks. Studies in northeast India demonstrate that oil palm agroforestry integrating pineapple, turmeric, or maize achieves the highest ecosystem carbon stocks, reaching 55.44 Mg C per hectare while maintaining crop productivity [68,69].

The carbon sequestration potential of agroforestry systems is well documented across multiple research contexts. Studies report that oil palm agroforestry systems can increase ecosystem carbon stocks by 20-40% compared to monoculture plantations, depending on the selection of companion species and system maturity. Carbon storage in agroforestry systems combining oil palm and agarwood ranges from 78.28 to 79.13 Mg C per hectare, substantially exceeding the carbon stocks of monocultures. Oil palm plantations themselves function as significant carbon sinks, with trees capable of absorbing up to 64.5 tons of carbon per hectare annually, according to some studies, exceeding tropical forest sequestration rates. The process of biosequestration through carbon storage in plant biomass and soil provides long-term climate benefits while production activities continue [6,69,70,71].

Despite demonstrated benefits, the adoption of agroforestry in commercial oil palm plantations remains limited to less than 5% due to multiple constraints. Producer concerns about oil palm yield competition from companion trees represent a significant

barrier, though research demonstrates that well-designed agroforestry can maintain palm oil yields at 90-95% of monoculture levels. Initial establishment costs, the complexity of multi-species management, long maturation periods for timber returns of 15-25 years, and a lack of extension support compound adoption challenges. Land tenure insecurity particularly constrains smallholder adoption of tree planting, as farmers operating on short-term leases have limited incentive to invest in long-rotation species. Enabling conditions for agroforestry expansion include appropriate species selection matching local ecology, technical guidance on spatial arrangements, market linkages for diversified products, secure land tenure, and recognition of carbon sequestration benefits through payment schemes [66,69,72].

### **Thematic Analysis: Decision Frameworks for Implementation**

#### **Multi-Criteria Decision Analysis Applications**

The literature reveals that, while sophisticated Multi-Criteria Decision Analysis methods have been extensively developed and applied in renewable energy and environmental management contexts, their explicit application to palm oil emissions-reduction decisions remains surprisingly limited. MCDA methods provide structured approaches for evaluating technology alternatives across multiple criteria, including technical performance, economic viability, environmental impact, and social acceptability. The methods address the inherent complexity of sustainability decisions, in which stakeholders with differing values must compare options across incommensurable dimensions. Common evaluation criteria identified across MCDA applications include emissions-reduction potential, technology readiness level, reliability and scalability, capital and operating costs, payback period, return on investment, co-benefits, including water quality and biodiversity, employment generation, community acceptance, regulatory compliance, and access to finance [39,73].

Studies applying MCDA methods to renewable energy selection in agricultural and industrial contexts demonstrate methodological sophistication that could inform decisions on palm oil technology. The Analytic Hierarchy Process structures decision problems hierarchically and derives criteria weights through pairwise comparisons, enabling systematic evaluation of alternatives while incorporating expert judgment. TOPSIS identifies alternatives closest to ideal solutions across all criteria, while VIKOR and COPRAS provide compromise rankings that balance group utility and individual regret. Hybrid approaches that combine subjective, expert-based weighting with objective, data-driven methods enhance robustness and reduce sensitivity to

individual judgment biases. Studies comparing MCDA methods applied to the same decision problem reveal that different techniques may yield varying rankings, highlighting the importance of method selection and sensitivity analysis [74].

A critical finding from this review is the limited integration of MCDA frameworks into actual palm oil industry decision-making despite their theoretical availability and demonstrated utility in related sectors. Only a handful of studies explicitly apply MCDA to palm oil technology decisions, and evidence of framework uptake by mills, plantation companies, or government agencies is scarce. This implementation gap suggests a need for simplified decision-making tools tailored to practitioners' contexts, capacity-building in decision-analysis methods, demonstration of the framework's value through pilot applications, and integration into certification and policy processes. The palm oil sector's unique characteristics, including the prevalence of smallholders, processing integration, certification requirements, and export orientation, warrant tailored decision frameworks rather than generic approaches [48,58].

#### **Economic Assessment and Cost-Benefit Analysis**

Economic viability fundamentally shapes technology adoption decisions, making a comprehensive cost-benefit analysis essential for informed investment choices. Economic assessments must account for direct costs, including capital investment, operating and maintenance expenses, training requirements, and transaction costs associated with certification and monitoring. Direct benefits encompass input cost savings from reduced fuel and fertilizer consumption, revenue generation from electricity sales and carbon credits, productivity improvements, and avoided compliance penalties. Externalities and co-benefits, including the social cost of carbon, environmental improvements, health benefits, and reputational advantages, are increasingly incorporated into comprehensive assessments. However, they are often difficult to quantify precisely [75,76].

Studies assessing emissions-reduction technologies in palm oil production report wide ranges in cost-effectiveness, measured as the marginal abatement cost per ton of CO<sub>2</sub>-equivalent avoided. Biogas capture systems show marginal abatement costs ranging from negative values indicating profitability without carbon pricing to approximately USD 20-40 per ton CO<sub>2</sub>-equivalent depending on energy prices, grid connectivity, and carbon credit availability. The economic viability of biogas systems depends critically on whether generated electricity can be sold to the grid or must be consumed on-site, with feed-in tariff policies significantly improving investment returns. Biomass briquetting pathways show marginal abatement costs of USD 15-30 per ton

CO<sub>2</sub>-equivalent, while advanced pyrolysis systems currently exhibit higher costs of USD 50-80 per ton CO<sub>2</sub>-equivalent, reflecting early-stage technology development [52,54,77].

Access to affordable finance emerges as a critical determinant of adoption, particularly for smallholders and independent mills facing capital constraints. High upfront costs, combined with payback periods of 5-10 years, exceed available capital and risk tolerance for many operators. Successful financing models identified in the literature include green bonds, concessional loans from development banks, blended finance that combines grants and commercial loans, carbon credit pre-financing that enables access to upfront capital, and cooperative-based group financing that spreads costs across multiple producers. Policy-driven economic incentives substantially influence technology viability through renewable energy feed-in tariffs, carbon pricing mechanisms, tax incentives for green investments, accelerated depreciation for environmental equipment, and direct subsidies for emissions reduction technologies [78].

### Life Cycle Assessment Decision Support

Life Cycle Assessment studies have generated substantial knowledge regarding the environmental impacts of palm oil production and the mitigation potential of technological interventions. LCA provides a comprehensive evaluation across the value chain, enabling the identification of emissions hotspots, the comparison of production scenarios, and the quantification of intervention benefits. Studies employing LCA methodology consistently identify POME management as the dominant emissions hotspot, accounting for 40-60% of total greenhouse gas impacts, depending on system boundaries and baseline practices. The production and application of nitrogen fertilizers represent the second major contributor, with N<sub>2</sub>O emissions from fertilizer accounting for 20-25% of plantation-level impacts [44,45].

Methodological choices significantly influence LCA results, creating challenges for comparison across studies and application to decision-making. System boundary definitions determining cradle-to-gate versus cradle-to-grave scope affect which processes are included and how impacts are allocated. Functional unit selection enables comparison across products but requires careful specification to ensure meaningful comparisons. Allocation methods distributing impacts among co-products, such as crude palm oil, palm kernel oil, and biomass residues, substantially influence per-product footprints. Land use change accounting is a particularly contentious methodological issue, with assumptions about direct versus indirect land use change and the carbon debt repayment period dramatically affecting results [44].

Despite the valuable environmental performance data it generates, integrating LCA into routine industry decision-making remains a persistent challenge. Methodological complexity requires specialized expertise that is not widely available within operating companies, particularly in smallholder operations. Data requirements for comprehensive LCA exceed what most producers routinely collect, necessitating significant investment in monitoring. Variability in results across studies due to methodological choices creates uncertainty about which findings to apply. The RSPO PalmGHG calculator is an effort to standardize greenhouse gas accounting and provide decision support, offering a simplified tool accessible to certified producers. However, data quality concerns, verification challenges, and limited uptake among non-RSPO members constrain the calculator's impact on broader industry decision-making.

### Barriers and Enablers Across Stakeholder Types

#### Large-Scale Plantations and Integrated Companies

Large integrated operations with substantial plantation and milling capacity face distinct adoption dynamics compared to smaller producers, with barriers primarily stemming from investment prioritization and organizational decision-making rather than from absolute resource constraints. Investment prioritization challenges arise as companies balance sustainability investments against core operational needs, expansion opportunities, and shareholder return expectations. Risk perceptions around emerging technologies at TRL 5-7 may discourage investment despite their long-term potential, as publicly listed companies face scrutiny for technology investments that do not generate near-term returns. Policy uncertainty affects long-term investment confidence, with regulatory changes, shifting market requirements, and evolving certification standards creating planning difficulties [80,81].

Despite these challenges, large-scale producers have significant enablers that support technology adoption. Access to capital and credit markets enables financing of substantial investments in biogas systems, biomass infrastructure, and precision agriculture platforms. Technical expertise and engineering capacity within corporate structures support technology evaluation, installation management, and operational optimization. Economies of scale make per-unit technology costs more manageable, with biogas systems and precision agriculture platforms becoming economically viable at plantation scales exceeding several thousand hectares. Direct connections to technology providers, equipment suppliers, and consulting firms facilitate access to solutions and technical support. The capacity to participate in carbon markets and sustainability certification creates additional revenue streams and market access advantages that improve technology economics [82].

## Independent Palm Oil Mills

Mid-sized independent mills face distinct challenges, including limited access to capital, infrastructure constraints, and narrower operating margins. Capital constraints bind more severely than for integrated companies, with investment requirements for biogas systems consuming substantial proportions of available capital. Limited grid access in rural locations complicates the monetization of renewable energy, as mills unable to export electricity to the grid capture lower value from biogas investments. Thinner margins reduce risk tolerance for new investments, making operators conservative about technologies with uncertain returns. Technical capacity gaps in the operation and maintenance of advanced technology require external support, which may be unavailable in remote locations [52,54,83].

Mills in jurisdictions with strong policy support demonstrate higher adoption rates than those in weaker policy environments, illustrating the pivotal role of policy for this stakeholder group. Malaysian mills subject to biogas mandates for new installations and benefiting from renewable energy feed-in tariffs show adoption rates of 60-70%, while Indonesian mills without equivalent incentives demonstrate rates of 20-30%. Policy instruments that improve the economics of technology, reduce regulatory uncertainty, and provide technical assistance can substantially accelerate adoption among independent mills. Financing mechanisms tailored to mill investment profiles, including equipment leasing and carbon credit pre-financing, address capital constraints while aligning repayment with benefit streams [84].

## Smallholder-Specific Barriers and Constraints

Smallholders operating plantations of less than 25 hectares face compounded barriers that make technology adoption extremely challenging without targeted support. Scale disadvantages mean that the fixed costs of technologies become prohibitively high per hectare at small scales. A biogas system economically viable for a 1,000-hectare operation becomes unaffordable for a 10-hectare smallholder, and even cooperative arrangements face coordination challenges. Fragmented landholdings with noncontiguous plots complicate the implementation of precision agriculture, requiring spatial continuity. Limited collateral constrains access to formal credit for sustainability investments, with only 10-15% of smallholders able to access loans for technology adoption [12,52,54].

Information and capacity barriers compound economic constraints for smallholders. Limited exposure to extension services, which regularly reach only 20-30% of smallholders,

results in low awareness of available technologies, their benefits, and implementation requirements. Digital literacy limitations impede the adoption of precision agriculture tools requiring data interpretation. Weak farmer organizations with low participation rates hamper collective action that could enable shared access to technology and group certification. RSPO certification remains inaccessible to most smallholders, with only 1-5% achieving certification due to complex requirements, documentation demands, and audit costs of USD 2,000-5,000. This certification exclusion excludes smallholders from premium markets and certification-linked support programs [85,86].

Successful approaches to smallholder technology adoption feature comprehensive support packages that address multiple barriers simultaneously. Group certification models reduce per-farmer costs by spreading audit expenses and shared infrastructure investments across producer groups. Cooperative-based equipment sharing enables access to technologies that are unaffordable at the individual scale. Output-based financing, delaying payment until harvest, aligns repayment with smallholder cash flow cycles. Satellite monitoring and digital reporting reduce documentation burdens while improving compliance verification. Mobile extension services and peer learning networks provide technical support, overcoming geographic isolation. These integrated approaches, which recognize the interconnected nature of smallholder constraints, are more effective than single-intervention strategies [76,87].

## Institutional Influences on Technology Adoption

Certification schemes, policy frameworks, and governance structures profoundly shape technology adoption dynamics in the palm oil sector, functioning as both drivers and barriers depending on design and implementation. RSPO certification establishes voluntary standards that have become de facto requirements for market access to sustainability-conscious buyers, creating pressure to adopt for certified and aspiring producers. Studies employing rigorous counterfactual analysis find that RSPO-certified plantations exhibit measurably lower environmental impacts, with certified palm oil generating approximately 35% fewer emissions per kilogram of processed oil than non-certified palm oil. These differences are attributed to factors such as reduced peatland development, higher crop yields, and advances in methane capture technology among certified producers [21,39].

However, certification effectiveness is constrained by structural limitations, including concentration among large operators, variable audit rigor, and incomplete market uptake of certified products. Approximately 80-90% of RSPO-certified plantations

are large-scale operations, leaving smallholders largely excluded from certification benefits and support mechanisms. ISPO in Indonesia and MSPO in Malaysia offer mandatory national certification alternatives with, in theory, broader coverage, though implementation challenges persist. Malaysia's mandatory MSPO achieved 70-75% coverage among independent smallholders through dedicated government support, whereas Indonesia's ISPO has certified fewer than 1% of smallholders, illustrating how institutional design and resource allocation shape effectiveness [88].

Policy instruments vary in effectiveness in promoting technology adoption depending on their design, implementation, and enforcement characteristics. Regulatory mandates requiring biogas installation for new mills have achieved 60-70% compliance in Malaysia when coupled with technical support and monitoring. Economic incentives, including feed-in tariffs for renewable electricity, substantially improve the economics of biogas systems, accelerating adoption in jurisdictions with such programs. However, chronic underfunding limits the extension service's reach to 20-30% of target populations, constraining the effectiveness of support programs. Critical institutional gaps include coordination deficits among government ministries with fragmented responsibilities, persistent exclusion of smallholders from frameworks designed around large-scale operations, enforcement weaknesses stemming from inadequate monitoring capacity, and underdeveloped financing mechanisms for investments {Formatting Citation}.

## Discussion

### Synthesis of Findings

This systematic review reveals that a robust portfolio of emissions-reduction technologies exists across palm oil production systems with substantial aggregate mitigation potential. Yet, significant gaps persist between technological availability, decision-making frameworks, and actual adoption outcomes. The technology landscape spans commercially mature interventions that can be deployed immediately, as well as emerging innovations that require ongoing development support. Biogas capture from POME is the highest-impact intervention, with demonstrated reductions of 65-90% in methane emissions, translating to 0.5-1.0 tons of CO<sub>2</sub>-equivalent per ton of crude palm oil. Renewable energy integration through biomass utilization enables an 80-90% reduction in fossil fuel dependence for mill operations. Precision agriculture yields 10-15% reductions in plantation-level emissions through optimized fertilizer application. Agroforestry systems enhance ecosystem carbon stocks by 20-40% while providing biodiversity co-benefits [24,50,91].

Critically, the review identifies a substantial gap between sophisticated decision frameworks available in the literature and their integration into actual industry practice. Multi-Criteria Decision Analysis, Life Cycle Assessment, and Technology Readiness Level assessment provide structured approaches for technology evaluation and selection. Yet, evidence of their application by palm oil producers, mills, or government agencies remains scarce. This implementation gap suggests that barriers extend beyond the availability of methods to encompass practitioners' awareness, capacity, and perceived relevance. The palm oil sector's unique characteristics, including the prevalence of smallholders, processing integration, certification requirements, and diverse stakeholder interests, warrant tailored decision frameworks rather than generic approaches imported from other contexts [13,92].

The review demonstrates that barriers to technology adoption are multidimensional and critically differentiated across stakeholder types. Large integrated companies possess resources, expertise, and market connections that enable adoption but face investment prioritization challenges and organizational complexity. Independent mills face capital and infrastructure constraints that policy incentives can substantially address. Smallholders face compounded barriers across economic, information, capacity, and institutional access domains, requiring comprehensive support packages that address multiple constraints simultaneously. Uniform technology promotion approaches fail because barriers differ fundamentally across these stakeholder types, indicating the need for differentiated intervention strategies [93,94].

Institutional factors profoundly shape adoption dynamics through certification requirements, policy instruments, and governance structures. RSPO certification demonstrates measurable environmental impacts among certified producers but remains concentrated in the hands of large operators, raising equity concerns. National mandatory certification schemes show variable effectiveness depending on government commitment, resource allocation, and enforcement capacity. Policy effectiveness depends on a coherent design that combines mandates with incentives and support, while addressing implementation challenges through adequate monitoring and enforcement [11,92].

### Implications for Policy and Practice

The findings generate implications across multiple stakeholder domains for accelerating climate action in the palm oil sector. For policymakers, the review supports implementing comprehensive policy portfolios that combine regulatory mandates, establish minimum requirements, provide economic incentives, improve technology economics, support programs, and build implementation capacity. Financing mechanisms specifically

designed for sustainability investments, including concessional credit, risk-sharing instruments, and smallholder-accessible products, address persistent capital constraints. Institutional coordination through dedicated implementation units with cross-ministerial mandates can overcome governance fragmentation that currently impedes coherent policy implementation. Enforcement strengthening through enhanced monitoring capacity, leveraging satellite remote sensing and digital reporting, improves compliance while reducing transaction costs [95].

For industry actors, including plantation companies and mills, the findings indicate prioritizing mature, high-impact technologies, such as biogas capture and renewable energy integration, that offer near-term emissions reductions alongside economic returns. Integration of emissions reduction into core business strategy and capital allocation processes, rather than treating it as a compliance obligation, enables systematic implementation aligned with operational planning. Investment in smallholder support programs, including contract farming, technical assistance, and input provision, enhances supply chain sustainability while addressing equity dimensions. Engagement in jurisdictional sustainability initiatives enables landscape-level coordination that individual actors cannot achieve on their own [54,89,96].

For research and development, the findings highlight the need for reducing technology costs and complexity to enhance accessibility for small-scale actors. Advancement of emerging technologies from pilot to demonstration scale through targeted funding and partnership development can expand the technology portfolio available for near-term deployment. The development and validation of simplified decision-support tools that practitioners can use without specialized expertise address the framework implementation gap. Participatory research, co-developing solutions with farmers and industry practitioners, ensures relevance and enhances the likelihood of adoption [47,76].

### Research Gaps and Future Directions

The systematic review identifies several critical research gaps warranting future investigation to advance climate action in palm oil production. First, while robust decision methodologies exist, their explicit application to palm oil emissions-reduction decisions remains limited, indicating the need for tailored framework development, validation with industry stakeholders, and the creation of simplified tools for practitioner use. Second, rigorous empirical research on effective interventions for smallholder technology adoption remains scarce despite a general understanding of barriers, suggesting a priority for experimental and quasi-experimental studies to evaluate intervention effectiveness. Third, most technology assessments occur under

controlled or optimal conditions, highlighting the need for long-term performance monitoring across diverse real-world operating conditions, including varying climates, feedstock characteristics, and management capacities [94,97].

Fourth, limited rigorous evaluation of policy and governance interventions constrains evidence-based policymaking, underscoring the need for comparative analysis of certification scheme effectiveness and for assessing innovative governance models. Fifth, emerging digital technologies, including satellite remote sensing, artificial intelligence, and blockchain for supply chain transparency, offer transformative potential yet remain underexplored in the context of palm oil. Sixth, understanding the financial mechanisms for scaling technology adoption requires a deeper investigation of the effectiveness of carbon credit programs, blended finance models, and payment-for-ecosystem-services schemes. Seventh, technology transitions raise equity concerns requiring explicit research attention to distributional effects, gender dimensions, and indigenous peoples' participation in climate action initiatives [46,76].

### Limitations

This review acknowledges several limitations that affect interpretation and generalizability. The geographic concentration of the literature heavily favors Malaysia and Indonesia, limiting the generalizability to emerging palm oil regions in Africa and Latin America, which have different institutional, ecological, and economic contexts. The focus on journal articles may exclude valuable practitioner knowledge, industry reports, and implementation experiences documented in grey literature. Restricting to English, Bahasa Indonesia, or Melayu-language publications may exclude relevant research published in other languages prevalent in the regions of production. The 2016-2026 timeframe ensures contemporary relevance but may miss foundational earlier work establishing baseline knowledge and initial technology assessments. Methodological heterogeneity across included studies, employing diverse research designs, complicates direct comparisons and quantitative synthesis. Limited longitudinal studies tracking technology adoption outcomes over extended periods constrain conclusions about the long-term effectiveness and sustainability of interventions [89,98].

### Conclusion

This systematic literature review comprehensively examines emissions-reduction technologies in palm oil production and the decision frameworks guiding their implementation, synthesizing evidence from 87 peer-reviewed studies published between 2016 and 2025. The findings reveal a robust technology portfolio capable of reducing emissions intensity by 60-75% relative to

baseline practices through the combined implementation of biogas capture, renewable energy integration, precision agriculture, and sustainable land management. Biogas capture from POME achieves 65-90% reductions in methane emissions, representing the highest-impact intervention. At the same time, commercially mature technologies at TRL 9 indicate that barriers to adoption are primarily economic, institutional, and social rather than technological.

However, the review identifies critical gaps between the availability of decision frameworks and their practical application, with sophisticated analytical methods, including Multi-Criteria Decision Analysis and Life Cycle Assessment, rarely integrated into industry decision-making despite their theoretical utility. Barriers to technology adoption differ fundamentally across stakeholder types, with smallholders facing compounded constraints that require comprehensive support packages that address economic, informational, and institutional dimensions simultaneously. Institutional factors, including certification schemes and policy frameworks, profoundly shape adoption dynamics but face implementation challenges in enforcement, coordination, and financing, requiring sustained governance attention.

The palm oil industry stands at a critical juncture where technological solutions exist to achieve substantial emissions reductions, yet adoption remains fragmented and inequitable. Realizing the sector's climate potential requires moving beyond technology development to integrated approaches that combine appropriate policies, accessible finance, technical support, and inclusive governance to reach all types of producers. The findings underscore that achieving net-zero palm oil production is technically feasible but contingent on addressing the complex socio-technical system within which technologies are embedded. As global climate targets demand transformation across all economic sectors, the palm oil industry's ability to implement available emissions-reduction technologies will significantly influence both agricultural climate contributions and the livelihoods of millions who depend on palm oil for economic development and sustenance.

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