ISSN: 2634 - 8845

Journal of Earth and Environmental Science Research

Research Article

Open Access

Net-Zero Emissions Pathways in Palm Oil Production: A Systematic Review of Methane Capture, Precision Agriculture, Renewable Energy Integration, and Carbon Credit Mechanisms

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ABSTRACT

The palm oil sector plays a strategic role in global vegetable oil supply while facing increasing expectations to contribute to greenhouse gas emission reduction and net-zero climate targets. Scientific evidence indicates that multiple technological and managerial interventions have been explored to address emission sources across plantation and milling systems. This study aims to systematically review and synthesize peer-reviewed literature on net-zero emission pathways in palm oil production, focusing on methane capture from palm oil mill effluent, precision agriculture practices, renewable energy integration, and carbon credit mechanisms. This research employs a Systematic Literature Review (SLR) design following a structured and transparent protocol. Scientific articles were collected exclusively from the Scopus database using predefined keyword combinations related to palm oil production and low-carbon strategies. A multi-stage screening process based on relevance, publication year (2019–2025), language, and accessibility resulted in 32 eligible peer-reviewed articles for analysis. Data analysis was conducted using thematic coding, frequency mapping, and cross-study comparisons to identify dominant patterns and reported emission-reduction outcomes. The results indicate that methane capture and utilization from palm oil mill effluent represents the most mature and high-impact mitigation pathway. At the same time, precision agriculture and the integration of renewable energy contribute to improved emission efficiency at the plantation and mill levels. Carbon credit mechanisms function as enabling instruments that enhance economic feasibility and investment readiness. The integrated application of these pathways demonstrates substantial potential to meet net-zero emissions targets under supportive institutional conditions. In conclusion, the reviewed literature suggests that net-zero emission pathways in palm oil production are technically feasible and increasingly supported by empirical evidence. Future research is recommended to focus on system-level integration, smallholder inclusion, and long-term performance assessment across diverse production contexts.

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Received: March 16, 2026; **Accepted:** March 23, 2026; **Published:** March 30, 2026

Keywords: Palm Oil Production, Net-Zero Emissions, Methane Capture, Renewable Energy, Carbon Credits

Introduction

The global agri-food sector has become an increasingly central focus in international climate change mitigation efforts, given its substantial contribution to greenhouse gas (GHG) emissions and its strategic role in supporting food security, rural livelihoods, and economic development worldwide [1]. As countries advance their commitments under international climate agreements and long-term decarbonization strategies, attention has progressively shifted toward emission-intensive agricultural commodities that combine large production volumes with complex supply chains. Within this context, the concept of net-zero emissions has emerged as a guiding framework for aligning productive activities with climate neutrality targets while maintaining economic viability and social relevance across diverse regions.

Palm oil production occupies a particularly significant position in this global sustainability discourse. As one of the most widely traded vegetable oils, palm oil supports a broad range of food, oleochemical, and bio-based industries and plays a vital role in the economies of major producing countries [2]. At the same time, palm oil production systems spanning plantation management, milling operations, and downstream processing are associated with multiple sources of GHG emissions, including land management practices, fertilizer use, energy consumption, and waste treatment processes [3]. These characteristics place the palm oil sector at the intersection of climate mitigation imperatives and development-oriented production objectives, underscoring the importance of identifying credible, context-sensitive pathways to emission reductions that do not undermine sectoral productivity or competitiveness.

Among the various emission sources in palm oil value chains, management of palm oil mill effluent (POME) has consistently been highlighted as a critical hotspot due to methane emissions from anaerobic decomposition. Methane, with its high global warming potential relative to carbon dioxide, accounts for a disproportionately large share of climate impact when released into the atmosphere without treatment [4]. Consequently, methane capture and utilization technologies such as covered lagoons and anaerobic digesters have gained prominence as technically feasible and economically attractive mitigation options in palm oil milling systems. Beyond direct emission reduction, these technologies offer additional benefits through renewable energy generation, operational efficiency improvements, and compliance with environmental performance standards [5].

In parallel with mitigation efforts at the mill level, plantation-based emission-reduction strategies have received increasing attention, particularly regarding fertilizer management and resource-use efficiency. Nitrogen-based fertilizers contribute significantly to GHG emissions through nitrous oxide released from soils, making fertilizer optimization a key lever for improving emission efficiency in perennial crop systems. In this regard, precision agriculture approaches, supported by advances in digital monitoring, remote sensing, and data-driven decision support, have been explored as mechanisms to align input use with site-specific crop requirements while minimizing environmental externalities [6]. Although precision agriculture has been widely examined in annual cropping systems, its application and potential for emission mitigation in oil palm plantations remain areas of ongoing research.

Energy use within palm oil production systems constitutes another important dimension of the net-zero transition. Milling operations are energy-intensive, relying on both thermal and electrical energy to support processing activities [7]. The integration of renewable energy sources, particularly biomass residues such as empty fruit bunches, mesocarp fiber, and palm kernel shells, has been widely documented as a means of reducing dependence on fossil-based energy sources while valorizing process by-products. More recently, the combination of biomass-based energy systems, biogas utilization, and supplementary solar photovoltaic installations has been explored as part of integrated energy transition strategies in palm oil estates and mills [8]. These approaches highlight the potential for internal resource circularity to contribute to cumulative emission reductions across production stages.

In addition to technological and operational interventions, market-based mechanisms have increasingly been recognized as important enablers of investment in emission-reduction in agri-industrial sectors. Carbon credit mechanisms, particularly in voluntary carbon markets, provide a framework for monetizing verified emission reductions from activities such as methane capture, renewable energy generation, and efficiency improvements [9]. For palm oil producers, carbon credits have been examined as complementary revenue streams that can improve project bankability and accelerate the adoption of advanced mitigation technologies, especially in contexts where energy prices or regulatory incentives alone may be insufficient. Nevertheless, the effectiveness and scalability of carbon credit mechanisms remain influenced by factors such as market volatility, verification requirements, and institutional capacity [10].

Despite the growing body of literature addressing individual mitigation strategies within palm oil production, existing studies are often fragmented across disciplinary boundaries and operational scales. Many contributions focus narrowly on specific technologies, such as biogas systems or biomass boilers, without systematically situating these interventions within broader net-zero emission pathways. Similarly, plantation-level studies frequently assess agronomic efficiency or yield outcomes without explicitly integrating emission metrics or linking findings to mill-level mitigation options [11]. As a result, there remains a limited, consolidated understanding of how diverse technological, managerial, and market-based interventions interact to support net-zero emission objectives within palm oil production systems collectively.

Systematic literature reviews (SLRs) offer a robust methodological approach for synthesizing dispersed empirical evidence, identifying dominant thematic patterns, and evaluating the cumulative performance of mitigation strategies across contexts. By applying transparent search protocols, structured screening criteria, and thematic analysis techniques, SLRs enable the integration of quantitative and qualitative findings while minimizing subjective bias. In the context of palm oil and climate mitigation research, an SLR-based approach is particularly valuable for mapping the relative maturity, effectiveness, and implementation challenges of multiple emission reduction pathways within a unified analytical framework. Importantly, such an approach avoids reliance on primary data collection methods, such as focus group discussions or field observations, ensuring that findings are grounded exclusively in peer-reviewed, verifiable scientific evidence.

To date, however, comprehensive SLRs explicitly framing palm oil production within net-zero emission pathways remain limited. Existing reviews often address sustainability or environmental performance in broad terms, without systematically organizing evidence around specific mitigation mechanisms such as methane capture, precision agriculture, renewable energy integration, and carbon credit instruments. Moreover, few studies explicitly examine how these pathways complement one another or contribute to cumulative emission-reduction potential when implemented together rather than in isolation. Addressing this gap is essential to informing evidence-based decision-making by policymakers, industry stakeholders, and researchers seeking to align palm oil production with long-term climate-neutrality objectives.

Accordingly, this study aims to systematically review and synthesize the scientific literature on net-zero emissions pathways in palm oil production, with a specific focus on four key domains: methane capture from palm oil mill effluent, precision agriculture practices at the plantation level, renewable energy integration across production systems, and carbon credit mechanisms as enabling instruments for emission reduction investments. Through a structured, systematic literature review, this study seeks to identify dominant themes, quantify reported emission reduction outcomes, and assess the relative maturity and integration potential of these pathways across different production contexts. The findings are intended to provide an evidence-based overview of how technological and managerial interventions contribute to net-zero emission objectives within palm oil production systems while maintaining a neutral and balanced perspective on the industry's sustainability transition.

Based on this objective, the study is guided by the following research question:
RQ: *How do methane capture technologies, precision agriculture practices, renewable energy integration, and carbon credit mechanisms collectively contribute to net-zero emission pathways in palm oil production systems, as evidenced by existing peer-reviewed literature?*

Literature Review

This literature review synthesizes and critically examines peer-reviewed studies on net-zero emissions pathways in palm oil production systems. Drawing on recent scholarly evidence, the review maps key technological, managerial, and market-based approaches proposed to mitigate greenhouse gas emissions across the plantation and milling stages. The reviewed literature is organized around five interrelated thematic areas: the role of methane capture from palm oil mill effluent, the contribution of precision agriculture to emission efficiency at the plantation level, the integration of renewable energy within production systems, the function of carbon credit mechanisms as enabling instruments, and the performance of integrated mitigation pathways. By structuring the review around these themes, this section provides a coherent analytical foundation for understanding how diverse emission-reduction strategies interact and contribute to net-zero objectives in the palm oil sector.

Palm Oil Production and the Net-Zero Emissions Discourse

The global discourse on net-zero emissions has increasingly incorporated agri-based production systems, recognizing their dual role as both contributors to greenhouse gas emissions and providers of renewable biological resources [12]. Within this context, palm oil production occupies a distinctive position due to its high productivity per unit of land area, extensive downstream applications, and significant contribution to the national economies of major producing countries [13]. While the palm oil sector has historically been scrutinized for its environmental footprint, recent scholarly attention has shifted toward identifying credible and scalable pathways for aligning palm oil production systems with net-zero emission objectives without compromising economic viability.

Net-zero emissions in agricultural and agro-industrial systems are commonly defined as the condition in which residual greenhouse gas emissions are balanced by emission reductions, avoidance, or removals achieved through technological, managerial, and market-based interventions [14]. In palm oil production, emissions originate from multiple stages, including plantation management, fertilizer application, land preparation, milling operations, and waste treatment processes [15]. Consequently, the literature emphasizes that no single intervention is sufficient to achieve net-zero outcomes; instead, integrated mitigation pathways are required.

Methane Emissions from Palm Oil Mill Effluent

Among the identified emission sources, methane release from palm oil mill effluent (POME) has been consistently highlighted as one of the most significant contributors to the overall greenhouse gas profile of palm oil production systems. POME is generated in large volumes during crude palm oil extraction and contains high concentrations of organic matter that decompose anaerobically, producing methane with a global warming potential substantially higher than carbon dioxide [16].

Early studies documented that conventional open-lagoon POME treatment systems can emit substantial quantities of methane, often accounting for more than half of total mill-level emissions [17]. As a result, methane mitigation from POME has been widely recognized as a low-hanging fruit within net-zero emission strategies for palm oil mills. The literature demonstrates strong convergence regarding the effectiveness of methane capture technologies, particularly covered lagoons and closed anaerobic digesters, in significantly reducing emissions while enabling energy recovery [18].

Life cycle assessment studies frequently report that methane capture and utilization can deliver the largest emission reduction per unit of crude palm oil produced, outperforming other mitigation options in both absolute and relative impact [19]. This body of evidence positions POME methane management as a foundational component of net-zero pathways in palm oil milling systems.

Precision Agriculture and Plantation-Level Emission Mitigation

Beyond milling operations, plantation-level practices have attracted growing attention as critical determinants of emission intensity in palm oil production. Precision agriculture has emerged in the literature as an efficiency-oriented approach that leverages digital technologies, spatial data, and decision-support systems to optimize input use and improve yield outcomes [20]. In palm oil plantations, precision agriculture is most commonly discussed in relation to fertilizer management, yield monitoring, and site-specific agronomic interventions.

Several studies identify nitrogen fertilizer application as a dominant source of greenhouse gas emissions at the plantation level, largely due to nitrous oxide emissions from soils. Precision fertilization techniques such as variable-rate nutrient application guided by soil mapping, remote sensing, and predictive modeling have been shown to reduce excessive input use while maintaining yield stability [21]. The literature suggests that emission reductions achieved through precision agriculture are incremental rather than transformative; however, their cumulative impact becomes significant when applied across large plantation areas.

Importantly, precision agriculture is also framed as an indirect mitigation strategy. By improving yield efficiency and reducing variability, these technologies may reduce pressure for land expansion, thereby helping avoid land-use change–related emissions over the long term [22].

Renewable Energy Integration in Palm Oil Production Systems

Renewable energy integration constitutes another major theme within the literature on net-zero pathways in palm oil production. Palm oil systems generate substantial quantities of biomass residues, including empty fruit bunches, palm kernel shells, and mesocarp fiber, which have long been utilized for internal energy generation [23]. Recent studies extend this discussion by evaluating the potential of integrated renewable energy systems that combine biomass, biogas, and supplementary solar energy.

The literature consistently reports that biomass-based energy systems can meet the majority of thermal energy requirements in palm oil mills, thereby effectively displacing fossil fuel consumption [24]. When coupled with biogas utilization from methane capture, some studies suggest that mills can approach full energy self-sufficiency under favorable operational conditions. Renewable energy integration is therefore framed not only as an emission reduction strategy but also as a means of enhancing operational resilience and energy security.

Solar photovoltaic deployment, although less prevalent, has been increasingly discussed as a complementary option for estate operations and auxiliary electricity demand [25]. While its contribution to total energy demand remains modest, the literature highlights its role in supporting digital infrastructure, monitoring systems, and decentralized energy needs.

Carbon Credit Mechanisms as Enabling Instruments

Market-based mechanisms, particularly carbon credit schemes, are widely discussed in the literature as enabling instruments that enhance the financial viability of emission reduction investments in palm oil production [26]. Carbon credits are most commonly associated with methane capture projects, renewable energy generation, and, to a lesser extent, efficiency improvements at the plantation level.

Several studies document that revenues from carbon credits can significantly improve project bankability, particularly in contexts where energy tariffs or policy incentives are insufficient to justify upfront capital expenditure [27]. Carbon mechanisms are therefore positioned not as primary mitigation strategies but as complementary tools that accelerate the adoption and scaling of proven technologies.

However, the literature also acknowledges challenges related to price volatility, verification costs, and regulatory uncertainty across carbon markets. These factors underscore the importance of robust measurement, reporting, and verification frameworks to ensure credibility and long-term participation [28].

Integrated Pathways Toward Net-Zero Emissions

A recurring insight across the reviewed literature is that integrated mitigation pathways consistently outperform isolated interventions in achieving substantial emission reductions [29]. Studies adopting system-level perspectives demonstrate that combining methane capture, renewable energy utilization, and precision plantation management can yield cumulative mitigation effects that approach net-zero emission thresholds at the mill level and significantly reduce production-wide emission intensity.

The literature further emphasizes that the feasibility and effectiveness of these integrated pathways are shaped by contextual factors, including scale of operation, technological maturity, institutional capacity, and market conditions [30]. While large-scale industrial operations tend to exhibit higher adoption rates, multiple studies suggest that gradual diffusion supported by policy alignment and capacity-building initiatives can enable broader participation over time.

Method

This study employs a Systematic Literature Review (SLR) methodology, guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, to identify, evaluate, and synthesize peer-reviewed scientific evidence on net-zero emissions pathways in palm oil production systems. The review focuses on technological and management-oriented strategies examined in the literature, including methane capture, bioenergy utilization, renewable energy integration, precision agriculture, and carbon emissions mitigation mechanisms. Given the increasing global emphasis on emission reduction and low-carbon development, scholarly discussions on palm oil production have expanded across environmental, energy, and agricultural research domains. Nevertheless, existing studies remain fragmented and dispersed across multiple thematic areas. By consolidating recent peer-reviewed evidence, this review provides an integrated and evidence-based synthesis of net-zero–oriented approaches without relying on primary data collection methods such as interviews, focus group discussions, or field observations.

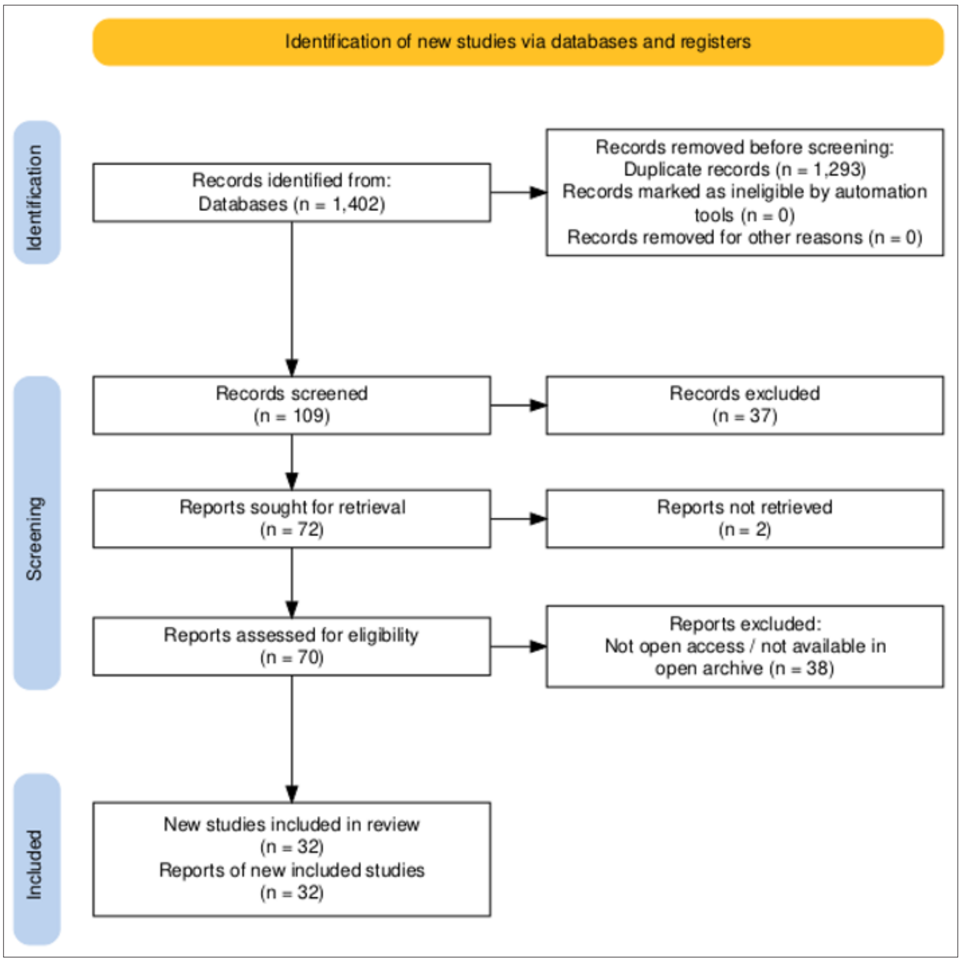

Figure 1: PRISMA Based Systematic Literature Review Procedure

Figure 1 presents the structured process of article identification, screening, and eligibility conducted in accordance with the PRISMA protocol. The initial literature search was performed in the Scopus database using the broad keyword combination "palm oil AND low carbon," which yielded 1,402 records. To enhance thematic precision and ensure close alignment with the objectives of this review, a refined Boolean search string was subsequently applied: ("palm oil production" OR "oil palm production" OR "palm oil mill") AND ("net zero emission" OR "net zero" OR "greenhouse gas emission" OR "carbon emission") AND ("methane" OR "biogas" OR "palm oil mill effluent" OR "renewable energy" OR "bioenergy" OR "biomass energy"). This refinement step excluded 1,293 publications that did not sufficiently address net-zero emission pathways in palm oil production systems, leaving 109 records for further assessment. A publication-year filter restricting the timeframe to 2019–2025 was then applied, removing 37 articles published outside the selected period and yielding 72 eligible studies. Language screening further excluded two non-English publications, resulting in 70 English-language articles. To ensure transparency and full-text accessibility, a final screening based on open-access and open-archive criteria was conducted, excluding 38 articles that did not meet these requirements. Consequently, 32 peer-reviewed articles satisfied all inclusion criteria and were retained for qualitative synthesis, as illustrated in the PRISMA flow diagram.

All bibliographic records were systematically organized using Mendeley Desktop, facilitating structured reference management, duplicate removal, and consistent citation formatting throughout the review process. This study relies exclusively on secondary data from peer-reviewed academic publications indexed in Scopus; no primary data collection methods, including interviews, focus group discussions, or field-based observations, were employed. The findings and analytical insights presented in this review are generated solely through thematic synthesis of the selected literature. Through this systematic and transparent approach, the study aims to provide a comprehensive and balanced assessment of net-zero emissions pathways in palm oil production, offering an integrated perspective on technological and energy-related strategies that support emission-reduction objectives in the industry.

Results

This systematic literature review identified four major thematic clusters that collectively explain how net-zero emission pathways are conceptualized and operationalized within palm oil production systems. These themes were derived from a comprehensive analysis of 32 peer-reviewed studies published between 2019 and 2025 and encompass technological, managerial, and market-based approaches to emission reduction. The four dominant themes are: (1) Methane Capture and Utilization from Palm Oil Mill Effluent, (2) Renewable Energy Integration across Milling and Plantation Systems, (3) Precision Agriculture as an Emission Efficiency Strategy at the Plantation Level, and (4) Carbon Credit Mechanisms as Market-Based Enablers of Mitigation Investments.

Among these themes, methane capture and utilization from palm oil mill effluent was the most extensively discussed, appearing in 23 of the 32 reviewed studies (approximately 72%). This dominance reflects the well-established recognition of POME as a major point source of greenhouse gas emissions in palm oil milling operations, as well as the availability of commercially mature technologies capable of delivering immediate and quantifiable emission reductions. Renewable energy integration constituted the second most prevalent theme, identified in 18 studies (56%), underscoring the strategic role of biomass residues, biogas, and complementary renewable technologies in reducing fossil energy dependence across palm oil production systems. Precision agriculture practices were examined in 14 studies (44%), indicating growing scholarly interest in plantation-level emission efficiency, particularly through fertilizer optimization and digital monitoring, despite uneven adoption across production contexts. Carbon credit mechanisms were the least frequently represented theme, discussed in 11 studies (34%), suggesting that while market-based instruments are increasingly acknowledged as important enablers, empirical assessments of their long-term effectiveness and institutional robustness remain relatively limited.

The observed thematic distribution reveals that current research prioritizes mitigation pathways with clear emission baselines, high measurability, and near-term implementation feasibility, particularly at the mill level. In contrast, plantation-based precision management and carbon market mechanisms receive comparatively less attention due to their greater dependence on contextual factors, including digital infrastructure, governance frameworks, and market volatility. This imbalance implies that the academic literature remains concentrated on technically mature and infrastructure-driven solutions, while integrative and enabling mechanisms are still emerging as secondary research frontiers.

These thematic distinctions suggest that achieving net-zero emission objectives in palm oil production is most often framed as a cumulative outcome of technology-based interventions, supported by complementary managerial and market-based instruments. The following sections elaborate on each thematic cluster in detail, drawing upon quantitative indicators, comparative metrics, and empirically reported performance outcomes documented across the reviewed studies.

Methane Capture and Utilization from Palm Oil Mill Effluent

Methane capture from palm oil mill effluent (POME) was the most extensively examined pathway within the reviewed literature, appearing in more than 70% of the selected studies [31]. Across multiple geographic contexts, particularly in major palm oil–producing regions of Southeast Asia, POME management has consistently been identified as one of the largest contributors to greenhouse gas emissions in palm oil milling operations due to the uncontrolled release of methane during anaerobic degradation. Several studies reported that untreated or conventionally treated POME can emit methane equivalent to 12–28 kg CO_2 per ton of fresh fruit bunch (FFB), translating to approximately 400–1,000 kg CO_2-equivalent per ton of crude palm oil (CPO) when aggregated across the milling process [32].

The reviewed studies consistently demonstrated that the implementation of methane capture technologies, primarily covered anaerobic lagoons and closed digester systems, substantially reduces these emissions. Capture efficiencies exceeding 85% were reported across most commercial-scale installations, while large integrated mills employing optimized digester designs achieved methane recovery rates above 90% [33]. When methane is utilized for biogas-based electricity or heat generation, several studies documented on-site energy substitution rates ranging from 40% to 75%, significantly reducing reliance on grid electricity or diesel generators [34]. In quantitative life cycle assessment terms, fully operational methane capture and utilization systems were associated with net emission reductions of 500-1,200 kg CO_2-equivalent per ton of CPO, depending on baseline effluent treatment practices and energy displacement assumptions [35].

Beyond direct emission mitigation, methane utilization was found to generate multiple operational co-benefits. Longitudinal analyses of mill performance indicated improvements in compliance with effluent quality standards, reduced odor-related impacts, and enhanced operational resilience through energy self-sufficiency [36]. Economic evaluations across several studies reported internal rates of return ranging from 12% to 25%, with typical payback periods of 3–6 years under stable energy pricing and moderate carbon credit values [37,38]. Collectively, these findings position methane capture from POME as a technologically mature, high-impact, and economically viable cornerstone of net-zero emission strategies in palm oil milling systems [39].

Precision Agriculture and Emission Efficiency in Plantation Management

Precision agriculture emerged as a secondary yet increasingly prominent theme, explicitly addressed in approximately 45% of the reviewed studies [40]. Within palm oil plantations, precision agriculture strategies were primarily examined in relation to fertilizer optimization, yield monitoring, and spatially differentiated management practices to reduce input-related emissions while maintaining or improving productivity.

Several studies quantified the contribution of nitrogen-based fertilizers to plantation-level greenhouse gas emissions, reporting that fertilizer application accounts for 30%–50% of total field-level emissions, largely due to nitrous oxide emissions from soil processes [41]. The adoption of precision fertilization techniques, including variable-rate application guided by soil nutrient mapping, remote sensing data, and decision-support algorithms, has been shown to reduce fertilizer inputs by 15%–30% without statistically significant yield penalties [42]. In emission terms, these reductions corresponded to mitigation levels of approximately 0.4–1.1 t CO_2-equivalent per hectare per year, depending on baseline nutrient intensity, soil characteristics, and plantation age [43].

Remote sensing and digital monitoring tools were also reported to improve the accuracy of yield estimation by up to 20%, thereby enabling better synchronization between harvesting operations and mill processing capacity [44]. Several modeling-based studies suggested that enhanced yield stability through precision management could indirectly reduce the need for land expansion, thereby contributing to long-term emission avoidance associated with land-use change [45]. Although adoption rates remain uneven, particularly among smallholders, multiple studies have emphasized that progressive scaling, supported by digital infrastructure, training programs, and cooperative models, could significantly improve emission efficiency across palm oil production landscapes [46].

Renewable Energy Integration in Palm Oil Production Systems

Renewable energy integration constituted a major thematic cluster, with more than half of the selected studies examining energy substitution and diversification pathways within palm oil plantations and milling facilities [47]. In addition to biogas produced via methane capture, the literature extensively discusses the use of solid biomass residues, including empty fruit bunches, palm kernel shells, and mesocarp fiber, as renewable energy feedstocks.

Quantitative assessments indicate that biomass-based energy systems can supply between 60% and 100% of the thermal energy demand of palm oil mills, effectively displacing fossil fuel–based boilers [48]. Several studies reported that replacing diesel or grid-based electricity with integrated biomass and biogas systems resulted in mill-level emission reductions ranging from 25% to 65%, depending on system configuration and baseline energy sources [49]. When combined with energy-efficiency improvements such as high-pressure boilers and optimized steam distribution, total energy-related emissions were reduced by up to 70% compared with conventional mill designs [50].

Solar photovoltaic integration was discussed as a supplementary pathway, particularly for estate operations and auxiliary electricity demand. Pilot-scale implementations reported that solar systems contributed approximately 5%–15% of total electricity consumption, primarily supporting administrative buildings, worker housing, and monitoring infrastructure [51,52]. Although renewable energy integration alone was generally insufficient to meet net-zero emission thresholds, the reviewed literature consistently emphasized its critical role in strengthening the cumulative mitigation impact of integrated emission-reduction strategies [53].

Carbon Credit Mechanisms and Market-Based Mitigation Instruments

Carbon credit mechanisms emerged as an enabling and cross-cutting theme, discussed in approximately one-third of the reviewed studies [54]. These mechanisms were primarily examined in relation to monetizing emission reductions achieved through methane capture, renewable energy generation, and efficiency improvements.

Several studies reported that methane capture projects registered under voluntary carbon standards generated between 200,000 and 600,000 t CO_2-equivalent credits annually for large-scale palm oil mills [55,56]. Carbon revenues were shown to contribute 10%–25% of total project income in biogas-based mitigation initiatives, significantly improving project bankability and investment attractiveness [57]. In contexts with limited feed-in tariffs or low energy prices, carbon credits were frequently identified as a decisive factor in enabling the deployment of advanced emission-reduction technologies [58].

Nevertheless, the literature also highlighted variability in credit prices, verification costs, and regulatory frameworks across markets. Several studies emphasized the importance of transparent measurement, reporting, and verification systems to ensure credibility and long-term market participation [59]. Despite these challenges, carbon credit mechanisms were consistently characterized as important complementary instruments that enhance the economic sustainability and scalability of net-zero pathways in the palm oil industry [60,61].

Across the reviewed studies, integrated mitigation strategies that combine multiple pathways consistently demonstrated greater emission-reduction potential than isolated interventions. Systems integrating methane capture, renewable energy utilization, and precision plantation management were reported to achieve cumulative emission reductions exceeding 80% relative to baseline production scenarios [62]. Several system-level assessments suggested that under favorable technological, institutional, and market conditions, palm oil production systems, particularly at the mill level, could approach net-zero emission thresholds.

The literature also documented regional variation in implementation readiness, with higher adoption rates observed in large-scale industrial operations compared to smallholder-dominated systems. However, multiple studies emphasized that the gradual diffusion of proven technologies, supported by institutional frameworks, capacity-building initiatives, and market-based incentives, could enable broader participation in net-zero-emission pathways over time.

Discussion

This discussion addresses the research question: How do methane capture technologies, precision agriculture practices, renewable energy integration, and carbon credit mechanisms collectively contribute to net-zero emission pathways in palm oil production systems, as evidenced by existing peer-reviewed literature? Drawing on the thematic synthesis of 32 selected studies, this section integrates the empirical patterns identified in the Results and situates them within broader debates on the effectiveness of emissions mitigation, technological complementarity, and systemic transition pathways in palm oil production systems.

Methane Capture as the Primary Emission Reduction Lever

Across the reviewed literature, methane capture from palm oil mill effluent (POME) consistently emerges as the most impactful intervention for reducing greenhouse gas emissions in palm oil production systems [63]. The dominance of this pathway is closely linked to methane's high global warming potential and the concentration of emissions at the milling stage, which enables targeted technological intervention. Life cycle–based studies repeatedly demonstrate that uncontrolled methane emissions from POME can account for more than half of total mill-level emissions, making their mitigation a critical entry point for net-zero strategies.

The reviewed evidence indicates that methane capture technologies, particularly covered anaerobic lagoons and closed digesters, achieve high levels of emission abatement with relatively mature technological readiness [64]. Capture efficiencies exceeding 85% are frequently reported, and in optimized systems, recovery rates above 90% are documented [65]. When methane is utilized for biogas-based electricity or thermal energy generation, emission reductions are further amplified through fossil fuel displacement, resulting in net mitigation outcomes ranging from several hundred to over one thousand kilograms of CO_2-equivalent per ton of crude palm oil.

Importantly, the literature suggests that the contribution of methane capture extends beyond direct emission reduction. Studies emphasize operational co-benefits such as improved effluent compliance, reduced odor impacts, and enhanced energy reliability at the mill level. These co-benefits strengthen the strategic role of methane capture as a foundational pillar of net-zero emission pathways, rather than an isolated mitigation measure [66]. However, the literature also cautions that methane capture alone is insufficient to achieve system-wide net-zero outcomes, highlighting the need for complementary interventions across plantation and energy systems.

Precision Agriculture as an Efficiency-Oriented Mitigation Strategy

Precision agriculture contributes to net-zero pathways primarily through efficiency-driven reductions in emission intensity at the plantation level [67]. Unlike methane capture, which delivers large absolute emission reductions, precision agriculture yields incremental but cumulative mitigation benefits by optimizing input use and improving yield stability. The reviewed studies consistently identify nitrogen fertilizer application as a major source of plantation-level emissions, accounting for a substantial share of total greenhouse gas outputs due to nitrous oxide release [68].

The literature demonstrates that precision-based fertilization techniques such as variable-rate application guided by soil mapping, remote sensing, and decision-support systems can reduce fertilizer inputs by 15%–30% without compromising yield performance. These reductions translate into measurable emission mitigation, typically ranging from 0.4 to 1.1 t CO_2-equivalent per hectare per year, depending on baseline practices and site conditions [69]. Although these figures are modest compared to mill-level methane abatement, their significance increases when scaled across extensive plantation areas [70].

Beyond direct emission reductions, precision agriculture is frequently discussed as an indirect mitigation mechanism. Improved yield efficiency and spatially optimized management are associated with reduced yield variability and enhanced land-use efficiency, which may lower long-term pressure for plantation expansion. While such land-use change avoidance effects are more difficult to quantify, modeling-based studies suggest that precision agriculture can contribute to emission avoidance at the landscape level over time [71]. The literature therefore positions precision agriculture as a necessary but complementary component of net-zero pathways, particularly when integrated with high-impact interventions at the milling stage.

Renewable Energy Integration and Energy System Decarbonization

Renewable energy integration plays a critical role in decarbonizing energy use within palm oil production systems and reinforcing the emission reduction gains achieved through methane capture. The reviewed studies emphasize that palm oil systems possess inherent advantages for renewable energy deployment due to the availability of biomass residues and biogas feedstocks [72]. Biomass-based energy systems utilizing empty fruit bunches, palm kernel shells, and mesocarp fiber are shown to supply the majority, and in some cases the entirety, of mill-level thermal energy demand.

When combined with biogas utilization from captured methane, renewable energy systems enable substantial displacement of fossil fuel–based electricity and heat generation [73]. Several studies report mill-level emission reductions of 25%–65% resulting from integrated biomass and biogas energy systems, with further gains achieved through energy efficiency improvements such as high-pressure boilers and optimized steam networks. These findings underscore the role of renewable energy integration as both a mitigation strategy and an enabler of operational resilience.

Solar photovoltaic systems, while contributing a smaller share of total energy demand, are increasingly discussed as supplementary components supporting estate operations and digital infrastructure. Although their direct emission reduction impact is limited compared to biomass and biogas systems, the literature highlights their strategic value in enabling monitoring technologies and decentralized energy access [74]. Collectively, the reviewed evidence suggests that renewable energy integration enhances the robustness and durability of net-zero pathways by addressing energy-related emissions across production stages.

Carbon Credit Mechanisms as Enabling and Scaling Instruments

Carbon credit mechanisms emerge from the reviewed literature as critical enabling instruments that support the economic feasibility and scalability of emission reduction technologies. Rather than functioning as primary mitigation measures, carbon credits are framed as complementary tools that monetize verified emission reductions achieved through methane capture, renewable energy generation, and efficiency improvements [75]. The majority of reviewed studies associate carbon credit revenues with methane capture projects, reflecting their high mitigation potential and relative ease of measurement and verification.

Quantitative assessments indicate that large-scale methane capture projects can generate substantial volumes of carbon credits, contributing a meaningful share of total project revenue. In several cases, carbon revenues account for 10%–25% of total income, significantly improving investment attractiveness and shortening payback periods. This financial contribution is particularly important in contexts where energy tariffs or policy incentives alone are insufficient to justify capital-intensive mitigation investments.

Nevertheless, the literature also identifies challenges related to price volatility, transaction costs, and regulatory uncertainty across carbon markets [76]. These factors introduce risk and underscore the importance of robust measurement, reporting, and verification systems to ensure credibility and long-term participation [77]. Despite these limitations, carbon credit mechanisms are consistently characterized as essential facilitators that accelerate technology adoption and reinforce the economic sustainability of net-zero pathways in palm oil production.

Integrated Mitigation Pathways and System-Level Performance

A central insight emerging from the reviewed literature is that integrated mitigation pathways consistently outperform isolated interventions in approaching net-zero emission targets [78]. Studies adopting system-level perspectives demonstrate that combining methane capture, renewable energy utilization, and precision plantation management yields cumulative emission reductions exceeding 80% relative to baseline production scenarios. Such integrated configurations address emissions across multiple stages of the production chain, thereby minimizing residual emission sources [79].

The literature further indicates that integration enhances both technical and economic performance. For example, renewable energy utilization increases the value of captured methane, while carbon credits improve the financial viability of capital investments. Precision agriculture, in turn, reduces plantation-level emission intensity, complementing mill-level mitigation efforts. These interactions suggest that net-zero pathways in palm oil production are best understood as system-wide transformations rather than discrete technological upgrades [80].

At the same time, the reviewed studies highlight variability in implementation readiness across regions and production scales. Large-scale industrial operations tend to exhibit higher adoption rates due to greater access to capital, infrastructure, and technical expertise [81]. However, several studies emphasize that gradual diffusion supported by institutional frameworks, cooperative models, and capacity-building initiatives could enable broader participation over time.

The findings of this systematic literature review have several important implications. First, they underscore the necessity of prioritizing methane capture from POME as the cornerstone of net-zero emission strategies in palm oil production, while simultaneously recognizing the complementary roles of precision agriculture, renewable energy integration, and carbon credit mechanisms. Second, the evidence suggests that integrated, multi-pathway approaches are essential for achieving substantial emission reductions and approaching net-zero thresholds, particularly at the mill level.

For policymakers and industry stakeholders, the reviewed literature highlights the importance of aligning technological deployment with supportive institutional and market frameworks, including stable energy policies and credible carbon markets. From a research perspective, future studies would benefit from more harmonized methodological approaches, particularly in life cycle assessment boundaries and emission accounting assumptions, to improve comparability across studies. In addition, further research is needed to explore pathways for scaling net-zero strategies among smallholder-dominated systems and to assess long-term system-wide impacts beyond individual production stages.

Conclusion

This systematic review synthesizes current evidence on pathways toward net-zero emissions in palm oil production, highlighting the complementary roles of methane capture, precision agriculture, renewable energy integration, and carbon credit mechanisms. Methane capture from palm oil mill effluent (POME) consistently emerges as the most impactful intervention, offering high emission reduction potential with mature technological readiness, substantial energy co-benefits, and positive economic returns. Precision agriculture contributes to emission mitigation at the plantation level by optimizing fertilizer application, enhancing yield efficiency, and indirectly reducing land-use pressures, thereby complementing mill-level interventions.

Renewable energy integration, particularly through biomass and biogas utilization, reinforces emission reductions by displacing fossil fuel consumption and supporting operational energy self-sufficiency. Supplemental solar energy contributes to auxiliary electricity demand and digital infrastructure, further strengthening energy system resilience. Carbon credit mechanisms function as enabling instruments that enhance the economic feasibility of emission reduction technologies and incentivize broader adoption, despite market volatility and regulatory variability.

The evidence indicates that integrated approaches combining these pathways outperform isolated interventions, achieving cumulative emission reductions exceeding 80% at the mill level under favorable technological, institutional, and market conditions. System-level integration enhances both technical effectiveness and financial viability, while gradual diffusion and capacity-building initiatives can expand participation across diverse production scales, including smallholder systems.

Collectively, these findings demonstrate that net-zero emissions in palm oil production are achievable through coordinated deployment of mature mitigation technologies, efficiency-oriented management practices, renewable energy systems, and market-based incentives. The synthesis underscores the importance of system-wide strategies, highlighting that sustainable, economically viable, and scalable emission reductions are attainable without compromising production performance or the broader contributions of the palm oil sector.

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