ISSN: 2634 - 8845

Journal of Earth and Environmental Science Research

SCIENTIFIC Research and Community

Review Article

Open Access

Life Cycle Assessment and Carbon Footprint Methodologies in the Palm Oil Supply Chain: A Systematic Review of Approaches, System Boundaries, and Emission Hotspots

Loso Judijanto

IPOSS Jakarta, Indonesia

ABSTRACT

A growing focus on openness in assessing environmental performance across agricultural supply chains has promoted the adoption of Life Cycle Assessment (LCA) and carbon footprint frameworks within the palm oil sector. This study systematically explores the implementation of these methodologies, placing particular emphasis on configuration choices, system boundary settings, and the identification of emission-intensive stages. A Systematic Literature Review (SLR) approach was employed, using the Scopus database as the primary source of peer-reviewed publications. The article selection followed a structured PRISMA-based screening process, resulting in 36 eligible studies published between 2020 and 2026. Data were collected exclusively from secondary sources and managed using reference organization tools to ensure consistency. The analysis was conducted through thematic synthesis, focusing on methodological patterns, boundary variations, and emission characteristics across the supply chain. The findings indicate that LCA, particularly attributional approaches, dominates current applications, while carbon footprint methods are frequently integrated to quantify greenhouse gas emissions. System boundary choices, especially the inclusion of land-use change, significantly influence emissions outcomes. Key emission hotspots are consistently identified at the plantation and milling stages, with reported emissions ranging from 0.8 to 4.5 t CO_2-eq per ton of crude palm oil depending on methodological assumptions. Despite variability, a gradual convergence toward more standardized practices is observed. In conclusion, methodological choices play a decisive role in shaping the outcomes of environmental assessment. Future research is encouraged to enhance methodological harmonization, integrate site-specific data, and expand system coverage to improve analytical consistency and transparency.

***Corresponding author**

Loso Judijanto, IPOSS Jakarta, Indonesia.

Received: May 08, 2026; **Accepted:** May 15, 2026; **Published:** May 22, 2026

Keywords: Life Cycle Assessment, Carbon Footprint, Palm Oil Supply Chain, System Boundaries, Emission Hotspots

Introduction

The growing global priority for sustainability in production systems has increased the need for reliable and transparent tools to assess environmental outcomes across interconnected agricultural supply chains. In this regard, Life Cycle Assessment (LCA) and carbon footprint approaches are commonly regarded as effective frameworks for assessing environmental impacts, particularly greenhouse gas (GHG) emissions, along various stages of production and distribution [1,2]. These methodologies provide structured frameworks that enable the systematic evaluation of resource use, emissions, and potential environmental trade-offs from upstream inputs to downstream outputs. As sustainability considerations become increasingly integrated into global policy, trade, and industry practices, the application of standardized environmental assessment tools has gained strategic importance in supporting evidence-based decision-making and improving analytical consistency across sectors [3,4].

Across agricultural systems, LCA and carbon footprint approaches have been increasingly applied, largely because of the complex, multi-stage production processes and the heterogeneity of inputs and outputs. Agricultural supply chains typically encompass land preparation, cultivation, harvesting, processing, transportation, and distribution, each of which contributes to overall environmental performance in distinct ways [5]. As a result, the ability to define system boundaries, allocate emissions across co-products, and identify critical stages of environmental impact has become central to the effective use of LCA-based approaches. At the same time, differences in methodological assumptions, data sources, and analytical frameworks can lead to variability in reported outcomes, highlighting the importance of systematic synthesis to enhance comparability and interpretability across studies [6].

In this context, the palm oil supply chain represents a particularly relevant case for the application of LCA and carbon footprint methodologies due to its integrated structure and its role in global agricultural production systems. The palm oil sector encompasses a series of interconnected stages, including plantation management, fresh fruit bunch (FFB) harvesting, milling, refining, and downstream product utilization. Each stage involves distinct material and energy flows, as well as specific emission sources, which collectively shape the supply chain's overall environmental profile [7]. The structured nature of this system provides a suitable framework for applying life–cycle–based assessments, enabling the identification of emission contributions across different stages while supporting more transparent, data-driven analytical approaches [8].

A growing body of scientific literature has explored the use of LCA and carbon footprint approaches within the palm oil sector, reflecting increased attention to environmental performance assessment and sustainability-oriented analysis. These studies have examined a range of methodological configurations, including attributional and consequential LCA, as well as various carbon accounting frameworks aligned with international standards. In addition, researchers have applied different system boundary definitions, such as cradle-to-gate and cradle-to-grave, to capture varying levels of supply chain complexity [9]. While this diversity of approaches contributes to methodological richness, it also introduces challenges for result comparability and consistency, as different assumptions can significantly influence emission estimates and hotspot identification.

In LCA studies, determining system boundaries is a central methodological step that influences the selection of processes to include in the analysis. Variations in boundary selection can lead to substantial differences in reported environmental impacts, particularly when certain stages, such as land use change or downstream processing, are included or excluded [10]. Similarly, the identification of emission hotspots, defined as stages or processes that contribute disproportionately to total emissions, depends on both data availability and analytical assumptions. As a result, understanding how different studies define and operationalize these methodological components is essential for interpreting findings and drawing meaningful conclusions.

Notwithstanding the growing body of studies on LCA and carbon footprint approaches in the palm oil sector, the literature remains heterogeneous and fragmented across methodologies, geographic contexts, and analytical dimensions. Some studies focus primarily on plantation-level emissions, while others emphasize processing or downstream stages, resulting in variation in analytical emphasis. Moreover, differences in data sources, emission factors, and allocation methods further contribute to heterogeneity in reported results. This dispersion of knowledge creates a need for a systematic and structured synthesis that consolidates current evidence, identifies common patterns, and clarifies methodological trends within the field.

To address this need, a systematic literature review (SLR) approach offers a methodologically rigorous and transparent framework that allows for comprehensive identification, evaluation, and synthesis of relevant scientific studies. Through a structured selection process and thematic analysis, SLR facilitates the integration of diverse findings into a coherent body of knowledge, while minimizing bias and enhancing reproducibility. The approach is strictly grounded in secondary data extracted from peer-reviewed sources, with no engagement in primary data collection, field observation, experimental procedures, surveys, or focus group discussions. By focusing on methodological synthesis rather than empirical data generation, SLR enables a deeper understanding of how analytical frameworks are applied and how methodological choices influence research outcomes.

In view of these considerations, this study undertakes a systematic analysis of the application of Life Cycle Assessment and carbon footprint methodologies in the palm oil supply chain, with emphasis on methodological design, system boundary determination, and emission hotspot identification. By synthesizing findings from peer-reviewed literature, the study seeks to provide a structured overview of current analytical practices, highlight areas of convergence and divergence, and contribute to the development of more consistent and transparent assessment frameworks. The objective is not to evaluate the sector from a normative perspective, but rather to clarify how existing methodologies are implemented and how they shape the interpretation of environmental performance.

To achieve this objective, the review is guided by two research questions that shape its analytical orientation.
RQ1: *How are Life Cycle Assessment and carbon footprint methodologies applied across different stages of the palm oil supply chain, including variations in methodological configurations and analytical approaches?*
RQ2: *How do differences in system boundary definitions and methodological assumptions influence the identification and characterization of emission hotspots within the supply chain?*
These research questions provide a structured basis for the subsequent analysis and are addressed through a systematic synthesis of the selected literature, forming the foundation for the discussion and conclusions presented in this study.

Literature Review

During the past decade, research on Life Cycle Assessment (LCA) and carbon footprint approaches in agricultural supply chains has risen notably, reflecting a greater emphasis on structured and transparent environmental performance assessment. Within this broader landscape, the palm oil supply chain has become a focal point of increasing academic interest due to its system-wide integration and its relevance to global production systems. Existing studies demonstrate considerable diversity in methodological approaches, variations in system boundary definitions, and differences in analytical focus, all of which influence how environmental impacts are quantified and interpreted. As a result, the current body of knowledge remains dispersed across multiple perspectives and methodological configurations. A structured synthesis of this literature is therefore essential to consolidate these varying approaches, clarify methodological patterns, and provide a more coherent understanding of how LCA and carbon footprint analyses are applied within the palm oil production and distribution chain.

Conceptual Foundations of Life Cycle Assessment and Carbon Footprint Methodologies

Life Cycle Assessment (LCA) is generally considered a comprehensive and structured methodology for evaluating environmental impacts throughout the complete life cycle of a product, from initial resource extraction to end-of-life disposal. In accordance with ISO 14040 and ISO 14044, LCA follows a four-stage framework comprising goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation [11]. This framework enables the systematic quantification of resource inputs and environmental outputs, including greenhouse gas emissions, energy use, and other impact categories. The flexibility of LCA allows it to be adapted to different sectors and analytical objectives, making it particularly suitable for complex systems such as agricultural supply chains.

Although related to LCA, carbon footprint analysis concentrates specifically on estimating greenhouse gas emissions in units of carbon dioxide equivalents (CO_2-eq). It is often conducted as a subset of LCA or as a standalone assessment aligned with frameworks such as the GHG Protocol and PAS 2050 [12]. The integration of carbon footprint methodologies within LCA enhances the ability to assess climate-related impacts while maintaining consistency with broader environmental evaluation frameworks. However, differences in methodological scope, emission-factor selection, and system boundary definitions can affect the comparability of results across studies.

A central methodological distinction in LCA is between attributional (ALCA) and consequential (CLCA) approaches. Attributional approaches aim to describe the environmental burdens associated with existing production systems, typically using average data, whereas consequential approaches assess the environmental consequences of changes in production or demand, often incorporating marginal data and system-wide interactions [13]. This distinction is particularly relevant in agricultural systems, where production dynamics and land use considerations can significantly affect environmental outcomes.

Application of LCA in Agricultural and Palm Oil Supply Chains

The application of LCA within agricultural systems has been driven by the need to evaluate environmental performance across multiple stages of production, each characterized by distinct inputs, processes, and outputs. In the context of palm oil, LCA has been employed to assess emissions associated with plantation management, harvesting, processing, and downstream activities. The integrated nature of the palm oil supply chain provides a structured framework for applying life cycle–based methodologies, allowing researchers to examine the distribution of environmental impacts across interconnected stages [14].

Studies focusing on palm oil systems often adopt a cradle-to-gate perspective, capturing emissions from plantation establishment through to crude palm oil (CPO) production. This approach enables the identification of key emission sources within upstream operations, including fertilizer application, energy use, and biomass management. Other studies extend the analysis to cradle-to-grave, incorporating downstream processes such as refining, transportation, and end-use, thereby providing a more comprehensive assessment of the overall product life cycle [15]. The choice of system boundary is closely linked to the study's objectives and has significant implications for the interpretation of results.

The use of carbon footprint analysis within the palm oil sector has also increased, reflecting the growing emphasis on climate-related metrics in sustainability assessments. These studies typically quantify total GHG emissions associated with specific functional units, such as per ton of CPO or per hectare of plantation area [16]. While carbon footprint studies provide valuable insights into emission intensity, their results are influenced by methodological assumptions, including emission factors, allocation methods, and data sources.

System Boundary Configurations and Methodological Implications

System boundary definition is a central component of LCA methodology, determining which processes are included in the analysis and, consequently, shaping the scope and outcomes of the assessment. The application of system boundaries in the palm oil literature commonly involves three main types: cradle-to-gate, cradle-to-grave, and gate-to-gate. Each approach reflects different analytical priorities and levels of system completeness [17].

Cradle-to-gate assessments are frequently used because they focus on production-stage emissions, which are often the primary concern in agricultural studies. These assessments typically include plantation operations, harvesting, transportation, and milling, providing a detailed understanding of upstream environmental impacts. In contrast, cradle-to-grave assessments extend the analysis to include downstream processes, offering a more comprehensive view of the product life cycle but requiring additional data and assumptions [18]. Gate-to-gate studies, while more limited in scope, allow for in-depth analysis of specific processes, such as palm oil milling or refining.

The inclusion of land use change (LUC) within system boundaries represents a particularly important methodological consideration. LUC can significantly influence total emission estimates, especially when converting high-carbon stock areas. However, the treatment of LUC varies across studies, with some including it as a core component of the analysis and others excluding it due to data limitations or methodological uncertainty [19]. This variation contributes to differences in reported results and underscores the need for transparency in methodological reporting.

Emission Hotspot Identification Across Supply Chain Stages

A central objective of LCA and carbon footprint studies is the identification of emission hotspots, defined as stages or processes that contribute disproportionately to total environmental impacts. Within the palm oil industry supply chain, several consistent hotspots have been identified across the literature, reflecting the structural characteristics of the production system.

Emissions at the plantation stage are commonly highlighted as significant, primarily due to fertilizer application, particularly nitrogen-based inputs that produce nitrous oxide (N_2O) [20]. Moreover, energy use during field operations and practices related to organic residue management contributes to the overall emissions profile. The magnitude of emissions at this stage is influenced by factors such as yield levels, input efficiency, and management practices.

Palm oil milling operations represent another significant emission source, particularly in relation to the management of palm oil mill effluent (POME). Methane emissions from POME are often identified as a key contributor to total emissions, especially in the absence of methane capture technologies [21]. The implementation of mitigation measures, such as biogas recovery systems, has been shown to substantially reduce emissions, highlighting the importance of technological interventions in improving environmental performance.

The inclusion of land use change in the analysis reveals it as a highly variable yet potentially significant source of emissions. The magnitude of LUC-related emissions depends on baseline land conditions, time horizons, and accounting methods, making it one of the most complex aspects of LCA in agricultural systems [22]. As such, the identification and interpretation of emission hotspots require careful consideration of methodological assumptions and data quality.

Methodological Variability and Emerging Standardization Efforts

Despite the growing body of literature on LCA and carbon footprint methodologies in the palm oil supply chain, significant variability remains across methodological approaches, data sources, and analytical frameworks. Variations in how system boundaries, functional units, allocation methods, and emission factors are defined contribute to inconsistent results, limiting the comparability of studies [23].

Allocation methods, in particular, play a critical role in determining how environmental burdens are distributed among co-products, such as palm oil and palm kernel. Common approaches include economic allocation, mass-based allocation, and energy-based allocation, each of which has implications for the interpretation of results [24]. The choice of allocation method is often influenced by study objectives and data availability, but it can also introduce variability in emission estimates.

Data quality and availability pose another key challenge, particularly regarding site-specific information on plantation practices and processing technologies. Many studies rely on secondary data from databases or literature sources, which may not fully capture local conditions. Such reliance can influence the accuracy and representativeness of LCA outcomes, indicating a need for strengthened data collection and reporting procedures [25].

To overcome these challenges, there is a growing emphasis on methodological standardization and transparency within the LCA community. The adoption of international guidelines, such as ISO standards and the GHG Protocol, has contributed to greater consistency in methodological approaches. At the same time, efforts to harmonize system boundary definitions, emission factors, and reporting practices are ongoing, reflecting the dynamic nature of this field [26].

Overall, the literature on LCA and carbon footprint methodologies in the palm oil supply chain reflects a maturing field characterized by increasing methodological sophistication and a growing emphasis on transparency and comparability. While variability in approaches remains, the convergence toward standardized practices suggests a gradual strengthening of the analytical framework for assessing environmental performance. This evolving body of knowledge provides a robust foundation for systematic synthesis, enabling a more integrated understanding of how methodological choices influence the evaluation of environmental impacts along palm oil supply chain stages.

Method

In this study, a PRISMA-guided Systematic Literature Review (SLR) methodology is adopted to systematically identify, examine, and synthesize existing scientific evidence on the application of Life Cycle Assessment (LCA) and carbon footprint approaches in the palm oil supply chain. The increasing adoption of life cycle–based approaches reflects a broader effort to enhance transparency and analytical consistency in assessing environmental performance across complex production systems. In the context of palm oil, LCA and carbon footprint analyses are widely used to assess emissions across interconnected stages, from upstream cultivation to downstream processing and distribution. These approaches provide structured mechanisms for quantifying greenhouse gas emissions, defining system boundaries, and identifying key stages that contribute to overall emission profiles. At the same time, variations in methodological choices, including boundary definitions and allocation procedures, can influence the comparability and interpretation of results across studies. Although a substantial body of literature has explored these analytical approaches, existing studies are dispersed across different scopes, assumptions, and system configurations. Hence, a systematic synthesis is required to integrate and structure current knowledge, particularly regarding methodological approaches, system boundary definitions, and emission hotspot identification within the palm oil supply chain. This review is conducted exclusively using secondary data derived from peer-reviewed scientific publications and does not involve primary data collection, field observation, experimental procedures, surveys, or focus group discussions.

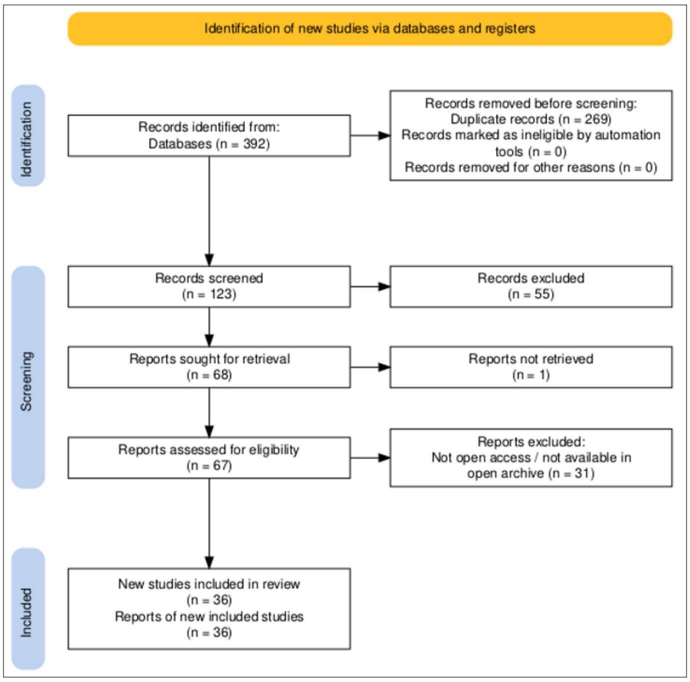

Figure 1: PRISMA-Based Screening Process for Article Selection

The flow diagram in Figure 1, based on the PRISMA framework, demonstrates the sequential process of identifying, screening, evaluating eligibility, and selecting the final set of articles. To include high-quality, peer-reviewed international sources, the literature search was conducted in the Scopus database. The preliminary search used the keyword combination “life cycle assessment” AND “palm oil”, which yielded 392 records covering a broad range of studies on life-cycle–oriented environmental assessments in palm oil systems. To improve the relevance and analytical focus of the dataset, a refined Boolean search strategy was subsequently applied using the combination (“*life cycle assessment” OR LCA OR “carbon footprint*”) AND (“*palm oil” OR “oil palm*”) *AND* (“*supply chain” OR “value chain” OR production*) *AND* (“*system boundary” OR “system boundaries” OR “greenhouse gas emissions” OR “emission hotspot” OR “hotspot analysis”)*. During this refinement stage, 269 articles were excluded for not aligning with the defined scope, leaving 123 records for further screening.

A time-based inclusion criterion was applied to retain studies published within the 2020–2026 period, ensuring that the review captures contemporary methodological innovations and analytical practices. This step led to the exclusion of 55 articles, leaving 68 studies that satisfied the time-based criterion. Language screening was subsequently applied to maintain consistency in analysis and interpretation, resulting in the exclusion of one non-English publication and reducing the dataset to 67 articles. A further filtering stage was conducted based on accessibility criteria, in which only articles categorized as open access or open archive were retained to ensure full-text availability and transparency in the review process. At this stage, 31 articles were excluded due to restricted access, resulting in a final dataset of 36 peer-reviewed articles that met all inclusion criteria.

To ensure consistency in citation management and bibliographic organization, all selected references were systematically compiled using Mendeley Desktop. The analytical process relies entirely on secondary data derived from Scopus-indexed publications, without incorporating interviews, field-based observations, experimental methods, or survey-based approaches. Through this structured PRISMA-based SLR process, the study provides a comprehensive synthesis of how LCA and carbon footprint methodologies are applied across the palm oil supply chain, with particular emphasis on methodological approaches, system boundary definitions, and the identification of emission hotspots, while maintaining a balanced and neutral perspective throughout the analysis.

Results

Findings from the synthesis of 36 peer-reviewed articles indicate five principal and interrelated thematic domains shaping current research on Life Cycle Assessment (LCA) and carbon footprint approaches in the palm oil supply chain. Across the reviewed literature, these thematic domains represent the principal areas through which environmental assessment frameworks, analytical configurations, and emission evaluation practices have been examined. The dominant themes identified include: (1) methodological approaches and LCA configurations, (2) system boundary definitions and their implications, (3) emission hotspot identification across supply chain stages, (4) variability in greenhouse gas (GHG) quantification and reporting, and (5) methodological challenges and harmonization needs. Although analytically distinct, these themes are conceptually interconnected and collectively reflect the evolving application of LCA-based approaches in assessing environmental performance within the palm oil supply chain.

The distribution of themes across the reviewed studies demonstrates varying levels of research emphasis. Methodological approaches and LCA configurations appear most frequently, discussed in approximately 78% of the studies (28 of 36 articles). Emission hotspot identification follows closely, identified in around 72% of the literature (26 articles). System boundary definitions and their implications are addressed in approximately 61% of the studies (22 articles). Methodological challenges and harmonization needs are discussed in about 68% of the literature (24 articles), indicating a growing awareness of limitations in current analytical practices. Meanwhile, variability in GHG quantification and reporting appears in approximately 55% of the studies (20 articles), reflecting increasing attention to inconsistencies in emission estimation and reporting practices.

The predominance of studies focusing on methodological configurations and emission hotspot identification reflects the central importance of these aspects in environmental assessment. Methodological design directly determines how system processes are represented and quantified, making it a primary concern in LCA-based studies. Similarly, the strong emphasis on emission hotspots indicates a practical orientation toward identifying the key stages in the supply chain that contribute most to overall emissions. These themes are explored in greater depth due to their immediate relevance to performance evaluation and their compatibility with existing analytical frameworks. In contrast, themes such as variability in GHG reporting and methodological harmonization, while increasingly recognized, are less frequently addressed due to their higher complexity and the need for more standardized datasets and assumptions. This imbalance suggests that current research is still transitioning from establishing core analytical frameworks toward improving consistency, comparability, and methodological robustness.

Overall, the thematic distribution indicates that current research on LCA and carbon footprint methodologies in the palm oil supply chain is driven primarily by efforts to refine analytical approaches and identify key emission sources, while gradually expanding toward addressing issues of standardization and data consistency. This pattern reflects a broader shift from methodological application toward methodological consolidation. A detailed explanation of each thematic domain is provided in the subsequent subsections.

Methodological Approaches and LCA Configurations

The reviewed studies demonstrate that LCA remains the predominant methodological framework for quantifying environmental impacts in the palm oil supply chain, with approximately 78% of the analyzed articles explicitly applying ISO 14040/14044-based LCA approaches [27]. Within this group, variations are observed in the type of LCA employed, including attributional LCA (ALCA), which accounts for nearly 64% of the cases, and consequential LCA (CLCA), representing about 14% [28]. The dominance of attributional approaches reflects a preference for assessing average environmental burdens associated with existing production systems, particularly in plantation and milling operations [29].

Carbon footprint analysis, often aligned with PAS 2050 or GHG Protocol guidelines, is applied either as a standalone method or integrated within LCA frameworks in approximately 42% of the reviewed studies [30]. These analyses primarily focus on quantifying CO_2-equivalent emissions (CO_2-eq), with reported values varying widely depending on system boundaries and methodological assumptions. For example, several studies report carbon footprint values ranging from 1.8 to 3.5 t CO_2-eq per ton of crude palm oil (CPO) under cradle-to-gate configurations, while others indicate lower values, between 0.9 and 1.6 t CO_2-eq per ton CPO, when excluding land use change components [31,32].

In terms of functional units, the majority of studies (approximately 72%) use mass-based units, such as per ton of fresh fruit bunches (FFB) or per ton of CPO, whereas a smaller proportion (around 18%) uses energy-based or land-based functional units [33]. This variation reflects differences in analytical objectives, with some studies focusing on production efficiency and others on energy performance or land-use intensity.

System Boundary Definitions and Their Implications

System boundary selection emerges as a critical determinant of analytical outcomes, with significant variation observed across the reviewed studies. Approximately 61% of the articles adopt a cradle-to-gate boundary, encompassing plantation, harvesting, transportation, and milling stages [34,35]. In contrast, about 25% extend the analysis to cradle-to-grave, incorporating downstream processes such as refining, distribution, and end-use [36]. A smaller subset (around 14%) focuses on gate-to-gate assessments, typically analyzing specific segments such as palm oil mills or processing facilities [37].

The inclusion or exclusion of land-use change (LUC) significantly affects emission estimates. Studies incorporating LUC report substantially higher emission values, often exceeding 4.0 t CO_2-eq per ton CPO in certain scenarios, whereas those excluding LUC generally report values below 2.0 t CO_2-eq per ton CPO [38-40]. This discrepancy highlights the sensitivity of LCA outcomes to boundary definitions and underscores the importance of transparent methodological reporting.

Moreover, the treatment of co-products, particularly palm kernel and palm kernel oil, introduces additional variability. Allocation methods vary across studies, with economic allocation used in approximately 46% of cases, mass-based allocation in 31%, and energy-based allocation in 23% [41]. These choices affect the distribution of environmental burdens and contribute to differences in reported emission intensities.

Emission Hotspots Across the Palm Oil Supply Chain

The identification of emission hotspots constitutes a central focus of the reviewed literature. Across the 36 studies, three primary hotspots are consistently identified: the plantation stage, palm oil milling, and land-use change processes.

The plantation stage accounts for approximately 35%–50% of total emissions in cradle-to-gate assessments, largely driven by fertilizer application, particularly nitrogen-based inputs, which contribute up to 60% of field-level emissions [42]. Direct and indirect nitrous oxide (N_2O) emissions are frequently highlighted as key contributors within this stage [43].

Palm oil milling operations represent the second major emission source, contributing approximately 25%–40% of total emissions [44]. Within this stage, palm oil mill effluent (POME) management is identified as a dominant emission source, accounting for up to 70% of milling-related emissions when methane capture technologies are not implemented [45]. Studies indicate that the adoption of methane recovery systems can reduce milling emissions by 45%–65%, demonstrating significant mitigation potential [46,47].

When included, land use change emerges as the most variable yet impactful emission source. In certain cases, LUC contributes more than 50% of total life-cycle emissions, particularly in high-carbon-stock areas [48]. However, several studies emphasize that emission outcomes are highly dependent on baseline land conditions and temporal assumptions, suggesting the need for context-specific interpretation [32].

Variability in Greenhouse Gas Quantification and Reporting

A notable finding across the reviewed studies is the considerable variability in reported GHG emissions, even under seemingly comparable system configurations. For cradle-to-gate assessments, total emissions range from approximately 0.8 to 4.5 t CO_2-eq per ton CPO, reflecting differences in system boundaries, data sources, and emission factors [49,50]. This variability is further influenced by regional factors, such as plantation management practices, yield levels, and technological adoption.

Emission factors for fertilizer-related emissions, particularly N_2O, vary across studies, ranging from 1% to 2.5% of applied nitrogen [51]. Similarly, assumptions regarding methane emissions from POME differ significantly, with reported emission factors ranging from 0.2 to 0.6 kg CH_4 per kg COD removed [52]. These discrepancies contribute to differences in overall emission estimates and highlight the need for standardized parameterization. Additionally, the use of secondary data dominates the reviewed literature, with approximately 83% of studies relying on databases such as Ecoinvent or region-specific inventories [53]. While this approach enhances comparability, it may also introduce uncertainties when local conditions are not fully captured.

Methodological Challenges and Harmonization Needs

The synthesis also identifies several methodological challenges that affect the robustness and comparability of LCA and carbon footprint studies in the palm oil sector. One of the primary challenges relates to the lack of harmonization in system boundary definitions and allocation methods, which complicates cross-study comparisons [54]. Approximately 68% of the reviewed studies explicitly acknowledge these inconsistencies as a limitation [55,56].

Data availability and quality represent another significant challenge. Around 57% of studies report limitations due to data gaps, particularly at the plantation level, where site-specific data are often scarce [57]. This reliance on generalized datasets can affect the accuracy of emission estimates.

Furthermore, only a limited proportion of studies (approximately 22%) conduct sensitivity or uncertainty analysis to assess the robustness of their results [58,59]. This suggests an area for methodological improvement, particularly in enhancing transparency and reliability.

Despite these challenges, the reviewed literature demonstrates a gradual convergence toward more consistent methodological practices, including greater use of standardized guidelines and improved transparency in reporting [59,60]. This trend indicates ongoing efforts within the research community to strengthen the analytical foundation of LCA and carbon footprint studies in the palm oil supply chain.

Overall, the results of this systematic literature review provide a comprehensive and data-rich synthesis of how LCA and carbon footprint methodologies are applied across the palm oil supply chain. The findings highlight both the diversity of methodological approaches and the emerging patterns that contribute to a more structured and transparent understanding of environmental performance, while maintaining a balanced perspective that reflects the sector's complexity and evolving nature.

Discussion

The findings synthesized from 36 peer-reviewed studies provide a comprehensive basis for addressing the two research questions concerning the use of Life Cycle Assessment (LCA) and carbon footprint methodologies across the palm oil supply chain, as well as the influence of methodological choices on emission hotspot identification. This discussion integrates the thematic patterns identified in the results and interprets them in relation to broader methodological developments in environmental assessment frameworks. Through this synthesis, the analysis clarifies how LCA and carbon footprint approaches are operationalized across different stages of the supply chain and how variations in system boundaries and analytical assumptions shape the characterization of greenhouse gas (GHG) emissions within the system.

Implementation of Life Cycle Assessment and Carbon Footprint Methods in the Palm Oil Supply Chain (RQ1)

The application of LCA and carbon footprint methodologies across the palm oil supply chain is primarily characterized by the use of structured, standardized frameworks that enable the systematic quantification of environmental impacts across interconnected production stages. Across the reviewed studies, LCA serves as the central analytical approach, most commonly aligned with ISO 14040/14044 standards, which provide a consistent methodological basis for defining system scope, compiling life cycle inventories, and conducting impact assessments [61,62]. This standardization facilitates comparability across studies while allowing for flexibility in adapting methodological configurations to specific analytical objectives.

A dominant pattern observed in the literature is the widespread use of attributional LCA (ALCA), particularly in studies of existing production systems. This approach is typically applied to quantify average environmental burdens associated with plantation operations, harvesting, transportation, and milling processes, where data availability is relatively robust, and process flows are well-defined [63,64]. The emphasis on attributional approaches reflects a methodological preference for describing current system performance rather than modeling broader system changes, thereby supporting benchmarking and performance evaluation within established operational contexts.

Carbon footprint methodologies are frequently integrated into LCA frameworks or applied as targeted assessments focused on GHG emissions. These approaches are often aligned with internationally recognized standards such as the GHG Protocol, enabling the quantification of emissions in CO_2-equivalent terms across clearly defined functional units [65]. Within the palm oil supply chain, carbon footprint analysis is commonly applied at the production and processing levels, where emission-intensity metrics such as emissions per ton of crude palm oil (CPO) or fresh fruit bunches (FFB) serve as a basis for comparative analysis and performance evaluation across different operational settings.

The application of these methodologies across supply chain stages reveals a multi-layered analytical structure. At the plantation level, LCA is used to capture emissions associated with land preparation, fertilizer application, and field operations, reflecting the importance of input-related processes in shaping overall environmental performance [66]. At the milling stage, the analytical focus shifts to energy consumption and waste management, particularly the treatment of palm oil mill effluent (POME), a significant source of methane emissions. Downstream stages, including refining and distribution, are incorporated in studies adopting broader system boundaries, although they are less frequently analyzed in detail due to increased data requirements and methodological complexity [67].

In addition to stage-specific applications, the reviewed literature demonstrates variability in methodological configurations, including the selection of functional units and allocation methods. Functional units are predominantly mass-based, facilitating consistency in output-related assessments, although alternative units are occasionally employed to capture specific analytical dimensions such as energy efficiency or land-use intensity [68]. Allocation methods, particularly economic and mass-based approaches, are used to distribute environmental burdens among co-products, reflecting the need to address the multi-output nature of palm oil production systems [69]. These methodological variations indicate that while LCA and carbon footprint frameworks provide a standardized foundation, their application remains adaptable to different research contexts and analytical priorities.

Overall, the findings suggest that LCA and carbon footprint methodologies are applied in a structured yet flexible manner across the palm oil supply chain, enabling the systematic assessment of environmental impacts while accommodating variations in data availability and analytical objectives. The consistent use of these approaches across the reviewed studies indicates their established role as core analytical tools for evaluating environmental performance within the sector.

Influence of System Boundary Definitions and Methodological Assumptions on Emission Hotspot Identification (RQ2)

In addressing the second research question, the reviewed literature demonstrates that system boundary definitions and methodological assumptions play a critical role in shaping the identification and characterization of emission hotspots within the palm oil supply chain. System boundaries determine the scope of processes included in the analysis, thereby influencing both the magnitude and distribution of reported emissions [70]. As such, variations in boundary selection are among the most significant sources of divergence in LCA and carbon footprint results.

A predominant approach observed in the literature is the use of cradle-to-gate system boundaries, which focus on upstream and midstream processes, including plantation operations, harvesting, transportation, and milling [71]. Within this boundary configuration, emission hotspots are most commonly identified at the plantation and milling stages. Plantation-level emissions are largely driven by fertilizer use, particularly nitrogen-based inputs that contribute to nitrous oxide (N_2O) emissions, while milling emissions are primarily associated with methane release from POME management [72]. This concentration of emissions within early supply chain stages reflects the analytical emphasis on production-related processes and highlights the importance of operational efficiency in shaping environmental outcomes.

In contrast, studies that adopt cradle-to-grave boundaries extend the analysis to downstream processes such as refining, distribution, and end use. While these stages typically contribute a smaller proportion of total emissions than upstream processes, their inclusion provides a more comprehensive understanding of life-cycle impacts and can shift the relative significance of identified hotspots [73,74]. This broader perspective allows evaluation of trade-offs across the entire supply chain, but it also introduces additional complexity in data requirements and modeling assumptions.

The inclusion of land use change (LUC) represents another critical methodological factor influencing emission hotspot identification. Studies that incorporate LUC often report significantly higher total emissions, with land conversion processes emerging as dominant contributors in certain contexts [75,76]. However, the treatment of LUC varies widely across the literature, with differences in baseline assumptions, time horizons, and accounting methods leading to substantial variability in reported results. This variability underscores the importance of transparent methodological reporting and highlights the sensitivity of emission estimates to underlying assumptions.

Methodological assumptions related to allocation methods also influence the distribution of emissions across supply chain stages. The choice between economic, mass-based, or energy-based allocation affects how environmental burdens are assigned to co-products, thereby influencing the relative contribution of different processes to total emissions [77]. For example, an economic allocation may assign a greater share of emissions to higher-value products, whereas a mass-based allocation distributes impacts based on physical output quantities. These differences can alter the perceived significance of emission hotspots and affect the interpretation of results.

In addition to allocation methods, variations in emission factors and data sources contribute to differences in hotspot characterization. Studies relying on region-specific data may yield more context-sensitive results, whereas those using generalizable databases may prioritize comparability across studies [78,79]. This trade-off between specificity and consistency reflects a broader methodological challenge within LCA and carbon footprint analysis, particularly in complex agricultural systems where local conditions play a significant role in shaping environmental outcomes.

Taken together, these findings indicate that emission hotspot identification is not solely determined by underlying physical processes but is also shaped by methodological choices related to system boundaries, allocation methods, and data inputs. As a result, differences in analytical configurations can lead to variations in both the magnitude and distribution of reported emissions, highlighting the need for careful interpretation and methodological transparency.

The results of this study provide several important insights with implications for both research and practice. From a methodological perspective, the consistent application of LCA and carbon footprint frameworks across the reviewed studies highlights their effectiveness as structured tools for assessing environmental performance within the palm oil supply chain. The ability of these methodologies to capture emissions across multiple stages and identify key hotspots supports more informed and transparent analytical processes. At the same time, the observed variability in methodological configurations underscores the importance of developing more harmonized approaches, particularly regarding system boundary definitions, allocation methods, and emission factor selection.

From a practical standpoint, the identification of emission hotspots at the plantation and milling stages suggests that targeted improvements in input efficiency, waste management, and process optimization can enhance environmental performance. The integration of methane capture technologies into POME management, for example, represents a well-documented opportunity to reduce emissions in the milling stage. These insights may enable stakeholders to prioritize key interventions and contribute to improved sustainability of production systems.

For future research, several areas warrant further investigation. First, there is a need for greater integration of downstream processes into LCA studies to provide a more comprehensive understanding of life-cycle impacts. Second, the development of standardized methodological frameworks would enhance comparability across studies and support the establishment of best practices. Third, increased use of site-specific data and advanced analytical techniques, such as dynamic modeling and high-resolution data integration, could improve the accuracy and relevance of LCA results. By addressing these areas, future research can contribute to the continued refinement of environmental assessment methodologies and support more consistent and transparent evaluation of supply chain performance.

Conclusion

This work provides a structured synthesis of how Life Cycle Assessment (LCA) and carbon footprint methodologies are applied across the palm oil supply chain and how methodological choices influence the identification of emission hotspots. The findings demonstrate that LCA, particularly in its attributional form, serves as the dominant analytical framework for evaluating environmental performance, supported by carbon footprint approaches that focus on quantifying greenhouse gas (GHG) emissions. These methodologies are applied across multiple stages of the supply chain, with the most consistent analytical coverage observed at the plantation and milling levels, where process flows are well-defined, and data availability is relatively robust. At the same time, variations in methodological configurations, such as functional units, allocation methods, and the integration of carbon footprint metrics, indicate that, while a standardized framework exists, its operationalization remains context-dependent and adaptable to different analytical objectives.

The synthesis further indicates that the application of these methodologies follows a structured yet flexible pattern. Plantation-level assessments primarily capture emissions associated with input use and field operations, while milling-level analyses emphasize energy use and waste management processes, particularly those related to palm oil mill effluent. Downstream stages are incorporated in broader system configurations, although their analytical representation is less frequent due to increased complexity and data requirements. This distribution of analytical focus suggests that current applications prioritize stages with the most direct and measurable contributions to environmental performance, while still allowing for expanded system coverage when required.

In relation to emission hotspot identification, the findings confirm that system boundary definitions and methodological assumptions play a decisive role in shaping analytical outcomes. Cradle-to-gate boundaries tend to concentrate emission hotspots within upstream and midstream stages, particularly plantation activities and milling operations, whereas cradle-to-grave approaches provide a more comprehensive perspective by incorporating downstream processes. The inclusion of land use change further amplifies total emission estimates and, in certain cases, shifts the relative dominance of identified hotspots. Additionally, methodological choices such as allocation approaches and emission factor selection significantly influence the distribution and magnitude of reported emissions, highlighting the sensitivity of results to underlying analytical assumptions.

Taken together, these findings indicate that emission hotspot characterization is not solely determined by physical processes within the supply chain, but is also shaped by how the system is defined and modeled. As a result, differences in methodological configurations can lead to variations in both the interpretation and comparability of environmental performance outcomes. This underscores the importance of transparency in reporting and careful consideration of methodological choices when interpreting LCA and carbon footprint results.

Overall, the synthesis reveals a gradual convergence toward more consistent application of LCA and carbon footprint methodologies, supported by established standards and improved reporting practices. At the same time, the observed variability across studies highlights the need for continued refinement and harmonization, particularly regarding system boundary definitions and key analytical parameters. These developments contribute to a more structured and transparent understanding of environmental performance within the palm oil supply chain, while maintaining flexibility to accommodate diverse research contexts and data conditions.

Future research can build on these findings by expanding the integration of downstream processes, enhancing the use of site-specific data, and further developing standardized methodological frameworks to improve comparability across studies. Additional efforts to incorporate dynamic modeling approaches and higher-resolution datasets may also strengthen the analytical precision of LCA applications. Through these advancements, the continued evolution of methodological practices can support more consistent, transparent, and informative environmental assessments within the palm oil sector.

References

1. Lakshmanan S, Yung YL (2024) Circular and Sustainable Practices of a Palm Oil Processing Complex. Palm Oil Industry: Plantation and Process Towards Circular Economy: 31-57
2. Schmidt J, Weidema IH (2026) A comparative life cycle assessment of palm oil—Differentiated by RSPO certified and non-certified, regionally, temporally, and by grower type. Sustain Prod Consum 64: 124-136.
3. Datta D, Barman D, Ghosal RK, Mandal E, Das B (2024) Plant Based Biofuels: A Sustainable Energy Source. Environmental Science and Engineering 2491: 167-185.
4. Mulya KS, Malvin Ma, Jian Ping Tan, Kun Sang, Siaw Ping Yeat, et al. (2026) Life cycle greenhouse gas assessment and geographic information system hotspot mapping of biofertilizer application on oil palm plantations. J Environ Manage 404: 129559.
5. Batlle EAO, Alisson Aparecido Vitoriano Julio, York Castillo Santiago, José Carlos Escobar Palácio, Edson Da Costa Bortoni, et al. (2022) Brazilian integrated oilpalm-sugarcane biorefinery: An energetic, exergetic, economic, and environmental (4E) assessment. Energy Convers Manag 268: 116066.
6. El Hathat Z, Venkatesh VG, Zouadi T, Sreedharan VR, Manimuthu A, et al. (2023) Analyzing the greenhouse gas emissions in the palm oil supply chain in the VUCA world: A blockchain initiative, Bus Strateg Environ 32: 5563-5582.
7. Agustin YE, Malvin Ma, Ning He, Swee Keong Yeap, Yew Woh Hui, et al. (2026) Valorization of Oil Palm Frond as a Renewable Carbon Source for Microbial Bioflocculant Production: A Green Approach to Agricultural Waste Management. Waste and Biomass Valorization. https://link.springer.com/article/10.1007/s12649-025-03458-y.
8. Agustira MA, Yani M, Prasetya H (2026) Life Cycle Assessment of Three Alternatives For the Application of Palm Oil Mill Effluent (Pome) Biogas Technologies in the Decarbonization Program of Palm Oil Mill. J Exp Biol Agric Sci 14: 85-96.
9. Meena LR, Kochewad SA, Prusty AK, Chandra Bhanu, Sanjeev Kumar, et al. (2022) Sustainable integrated farming system model for small farm holders of Uttar Pradesh. Indian J Agric Sci 92: 1080-1085.
10. Boonrod B, Chaiwat Prapainainar, Phavanee Narataruksa, Angsana Kantama, Worayut Saibautrong, et al. (2017) Evaluating the environmental impacts of bio-hydrogenated diesel production from palm oil and fatty acid methyl ester through life cycle assessment. J Clean Prod 142: 1210-1221.
11. Musikavong C, Gheewala SH (2017) Assessing ecological footprints of products from the rubber industry and palm oil mills in Thailand. J Clean Prod 142: 1148-1157.
12. Boonrod B, Prapainainar P, Varabuntoonvit V, Sudsakorn K, Prapainainar C (2021) Environmental impact assessment of bio-hydrogenated diesel from hydrogen and co-product of palm oil industry. Int J Hydrogen Energy 46: 10570-10585.
13. Su G, Peng Jiang, Hwai Chyuan Ong, Jiahua Zhu, Nor Aishah Saidina Amin, et al. (2023) Co-production of biochar and electricity from oil palm wastes for carbon dioxide mitigation in Malaysia. J Clean Prod 423.
14. Fidan M, Nevzat Konar, Ilyas Atalar, Ibrahim Palabiyik, Cihat Güner, et al. (2025) Comparative life cycle assessment of deep frying and tunnel drying in instant noodle manufacturing: Environmental trade-offs and hotspot identification. Sci Total Environ 1008.
15. Wahyono Y, Hadiyanto H, Gheewala SH, Budihardjo MA, Adiansyah JS (2022) Evaluating the environmental impacts of the multi-feedstock biodiesel production process in Indonesia using life cycle assessment (LCA). Energy Convers Manag 266: 115832.
16. Amasawa E, Yamanishi T, Nakatani J, Hirao M, Sato S (2021) Climate change implications of bio-based and marine-biodegradable plastic: Evidence from poly(3-hydroxybutyrate-co-3-hydroxyhexanoate). Environ Sci Technol 55: 3380-3388.
17. Rosmeika R, Irhan Febijanto, Delfi Fatina Soraya, Hermawan Febriansyah, Febrian Isharyadi, et al. (2025) Environmental impact of palm cooking oil: a case study in Sumatra, Indonesia. Environ Sci Pollut Res 32: 24839-24857.
18. Haryati Z, Subramaniam V, Noor ZZ, Loh SK, Aziz AA (2021) Complementing social life cycle assessment to reach sustainable development goals - A case study from the malaysian oil palm industry. Chem Eng Trans 83: 331-336.
19. Moreira Rodrigues RC, Da Silva Ramos N, Gonçalves FB, Erasmo EAL (2023) Environmental and energy performance assessment of the agricultural phase of the production of fresh oil palm. Agroenergy: Renewable and Sustainable Energy 15-25.
20. Lee JTE, Muhammad Usman Khan, Hailin Tian, Alvin WL Ee, Ee Yang Lim, et al. (2020) Improving methane yield of oil palm empty fruit bunches by wet oxidation pretreatment: Mesophilic and thermophilic anaerobic digestion conditions and the associated global warming potential effects. Energy Convers Manag 225.
21. Patel K, Singh SK (2024) Sustainable biodiesel from used cooking oil: a comparative life cycle, energy, and uncertainty analysis. Environ Dev Sustain 1-26.
22. Phuang ZX, Lin Z, Liew PY, Hanafiah MM, Woon KS (2022) The dilemma in energy transition in Malaysia: A comparative life cycle assessment of large scale solar and biodiesel production from palm oil. J Clean Prod 350: 131475.
23. Goh KC, Tonni Agustiono Kurniawan, Abdulkareem AlSultan G, Mohd Hafiz Dzarfan Othman, Abdelkader Anouzla, et al. (2025) Innovative circular bioeconomy and decarbonization approaches in palm oil waste management: A review. Process Saf Environ Prot 195: 106746.
24. Anyaoha KE, Zhang L (2021) Renewable energy for environmental protection: Life cycle inventory of Nigeria's palm oil production. Resour Conserv Recycl 174: 105797.
25. Ranjetha K, Alengaram UJ, Alnahhal AM, Karthick S, Zurina WJW, et al. (2022) Towards sustainable construction through the application of low carbon footprint products. Mater Today Proc 52: 873-881.
26. Rivera-Méndez YD, Rodríguez DT, Romero HM (2017) Carbon footprint of the production of oil palm (Elaeis guineensis) fresh fruit bunches in Colombia. J Clean Prod 149: 743-750.
27. Saharudin DM, Jeswani HK, Azapagic A (2024) Biochar from agricultural wastes: Environmental sustainability, economic viability and the potential as a negative emissions technology in Malaysia. Sci Total Environ 919: 170266.
28. De Lapuente Díaz de Otazu RL, Akizu-Gardoki O, De Ulibarri B, Iturrondobeitia M, Minguez R, et al. (2022) Ecodesign coupled with Life Cycle Assessment to reduce

the environmental impacts of an industrial enzymatic cleaner. Sustain Prod Consum 29: 718-729.

29. Manikandan SK, Maria Hasnain, Rida Zainab, Fouad L Ridouane, Aseela Al Moalla, et al. (2026) Treating palm oil mill effluent (POME): Opportunities, challenges, and sustainable practices. Environ Technol Innov 42.
30. Yahya SA, Iqbal T, Omar MM, Ahmad M (2021) Techno-economic analysis of fast pyrolysis of date palm waste for adoption in Saudi Arabia. Energies 14.
31. Chiriacò MV, Galli N, Santini M, Rulli MC (2024) Deforestation and greenhouse gas emissions could arise when replacing palm oil with other vegetable oils. Sci Total Environ 914: 169486.
32. Siregar K, Sholihati Sholiati, Intan Sofiah, Try Miharza, Roy Hendroko Setyobudi, et al. (2020) Review of Implementation Life Cycle Assessment for Biodiesel Production from Palm Oil (Elaeis guineensis Jacq.) in Indonesia. E3S Web of Conferences 190.
33. Niu Y, Starrett N, Ahmad MI, Wang S, Li Y, et al. (2026) Sustainability Assessment of Bioethanol from Food Industry Lignocellulosic Wastes: A Life Cycle Perspective. Sustain 18.
34. Khasanah N K, Van Noordwijk M, Slingerland M, Sofiyudin M, Stomph D, et al. (2020) Oil palm agroforestry can achieve economic and environmental gains as indicated by multifunctional land equivalent ratios. Front Sustain Food Syst 3: 122.
35. Yudha YS, Biney M, Tarigan SD (2024) Life cycle assessment of oil palm plantation in Riau province: Evaluating environmental impacts. IOP Conference Series: Earth and Environmental Science. https://iopscience.iop.org/article/10.1088/1755-1315/1379/1/012008.
36. Sun K, Liu H, Fan H, Liu T, Zheng C (2021) Research progress on the application of feed additives in ruminal methane emission reduction: A review. Peer J 9.
37. Barros Lovate Temporim R, Cavalaglio G, Petrozzi A, Coccia V, Cotana F, et al. (2022) Life Cycle Assessment of Cynara cardunculus L. -Based Polygeneration and Biodiesel Chains. Sustain 14.
38. Ruiz-Alvarez E, Arley David Zapata-Hernández, Alexandre Cooman, Nolver Arias Arias, David Arturo Munar-Flores, et al. (2026) Labour demand, economic profitability, energy efficiency, and greenhouse gas emissions: A comparative assessment of mechanization scenarios across yield gradients in oil palm crops in Colombia. OCL - Oilseeds Fats Crop Lipids 33.
39. Pipitone G, Zoppi G, Pirone R, Bensaid S (2023) Sustainable aviation fuel production using in-situ hydrogen supply via aqueous phase reforming: A techno-economic and life-cycle greenhouse gas emissions assessment. J Clean Prod 418: 138141.
40. Sinoh SS, Ibrahim Z, Othman F (2021) Life cycle assessment of palm oil clinker as a binder and aggregate replacement in concrete. J Oil Palm Res 33: 151-170.
41. Santoso AD, Evi Sribudiani, Atien Priyanti, Dwi Yulistiani, Hotmatua Daulay, et al. (2025) Sustainable utilization of palm oil industry by-products for livestock feed: A digestibility and environmental assessment. Case Stud Chem Environ Eng 12.
42. Bordignon F, Angela Trocino, Enrico Sturaro, Silvia Martínez-Llorens, Ana Tomas-Vidal, et al. (2023) Fish oil substitution with vegetable oils in diets for greater amberjack (Seriola dumerili): A consequential life cycle assessment approach. Aquaculture 563.
43. Sui Y, Mohareb E, Xue L, Liu G, Smith ST (2025) Mitigating environmental impacts of chicken production – The role of Co-product valorisation. J Clean Prod 528.
44. Sari DAP, Nikmah M, Sasongko NA (2023) Life Cycle Assessment in The Production Process of Crude Palm Oil (Cpo) On Palm Oil Plantation and Mills. Int J Geomate 25: 177-184.
45. Adlan CA, Hanssen SV, Luchtenbelt H, Hendriks C, Doelman JC, et al. (2025) Emissions Footprints of Agriculture Around the World 1970–2020: Decreasing Land Conversion, Regional Exceptions and Increasing Management Intensity. Glob Chang Biol 31.
46. Prasetya H, Apriyanto H, Agustina L (2023) Determination of optimum technologies implementation scenarios toward net zero emissions in palm oil biodiesel production. IOP Conference Series: Earth and Environmental Science. https://iopscience.iop.org/article/10.1088/1755-1315/1187/1/012029.
47. Munar-Flórez DA, Nidia Elizabeth Ramírez-Contreras, Jorge Alberto Albarracín-Arias, Phanor Arias-Camayo,Víctor Rincón-Romero, et al. (2025) Decarbonizing Aviation: The Low-Carbon Footprint and Strategic Potential of Colombian Palm Oil for Sustainable Aviation Fuel. Energies 18.
48. Kikuchi Y, Torizaki N, Tähkämö L, Enström A, Kuusisto S (2022) Life cycle greenhouse gas emissions of biomass- and waste-derived hydrocarbons considering uncertainties in available feedstocks. Process Saf Environ Prot 166: 693-703.
49. Sato I, Listyanto T, Susanti A, Kayo C (2025) Greenhouse gas emissions reduction potential of biomass power generation in Japan using empty fruit bunch pellets from Indonesia. Tropics 34: 11-22.
50. Beyer R, Rademacher T (2021) Species richness and carbon footprints of vegetable oils: can high yields outweigh palm oil's environmental impact? Sustainability 13: 1813.
51. Cooper HV, Evers S, Aplin P, Crout N, Dahalan MPB, et al. (2020) Greenhouse gas emissions resulting from conversion of peat swamp forest to oil palm plantation. Nat Commun 11: 407.
52. Alcock TD, Salt DE, Wilson P, Ramsden SJ (2022) More sustainable vegetable oil: Balancing productivity with carbon storage opportunities. Sci Total Environ 829: 1-14.
53. Akhbari A, Wen LC, Onn CC, Annuar S, Ibrahim S (2025) Comparative life cycle assessment (LCA) of up-flow anaerobic sludge blanket fixed-film (UASFF) reactor and continuous stirred tank reactor (CSTR) for biohydrogen production treating palm oil mill effluent (POME). IOP Conference Series: Earth and Environmental Science. https://iopscience.iop.org/article/10.1088/1755-1315/1560/1/012004.
54. Kosai S, Sazalina Zakaria, Hang Seng Che, Md Hasanuzzaman, Nasrudin Abd Rahim, et al. (2022) Estimation of Greenhouse Gas Emissions of Petrol, Biodiesel and Battery Electric Vehicles in Malaysia Based on Life Cycle Approach. Sustain 14.
55. Castillo-Gracia LÁ, Urbina-Suarez NA, González-Delgado ÁD (20255) Bibliometric and Co-Occurrence Study of the Production of Bioethanol and Hydrogen from African Palm Rachis (2003–2023). Sustain 17.
56. Xu H, Lee U, Wang M (2020) Life-cycle energy use and greenhouse gas emissions of palm fatty acid distillate derived renewable diesel. Renew Sustain Energy Rev 134: 110144.
57. Ocampo Batlle EA, José Carlos Escobar Palacio, Electo Eduardo Silva Lora, Edson Da Costa Bortoni, Luiz Augusto Horta Nogueira, et al. (2021) Energy, economic, and environmental assessment of the integrated production of palm oil biodiesel and sugarcane ethanol. J Clean Prod 311: 127638.
58. Jain A, Padmanaban M, Hazra J, Guruprasad R, Godbole S, et al. (2024) Data-driven decarbonization framework with machine learning. Environ Data Sci 3.

59. Anuar H, Siti Munirah Salimah Abd Rashid, Nurfarahin Mohd Nordin, Fathilah Ali, Yose Fachmi Buys, et al. (2021) Potential Of Fabrication Of Durian Skin Fiber Biocomposites For Food Packaging Application Through The Electricity Impact Analysis. IIUM Eng J 22.
60. Luanwuthi S, Iamprasertkun P, Akkharaamnuay T, Kunyawut C, Phukhrongthung A, et al. (2024) Techno-economic and Environmental Assessment of Activated Carbon Electrodes for Supercapacitors from Oil Palm Leaves. ACS Sustain Chem Eng 12: 14446-14458.
61. Ocampo Batlle EA, York Castillo Santiago, Osvaldo José Venturini, José Carlos Escobar Palacio, Electo Eduardo Silva Lora, et al. (2020) Thermodynamic and environmental assessment of different scenarios for the insertion of pyrolysis technology in palm oil biorefineries. J Clean Prod 250: 119544.
62. Bhatia SK, Patel AK, Ravindran B, Yang YH (2025) Renewable bioenergy from palm oil mill effluent (POME): A sustainable solution for net-zero emissions in palm oil production. J Water Process Eng 70: 107136.
63. Shamsudin NA, Sahid I, Mokhtar A, Muhamad H, Ahmad S (2018) Life cycle inventory of oil palm lumber production: A gate-To-gate case study. AIP Conference Proceedings 1940.
64. Suwannarat S, Teerayut Leevijit, Seppo Karrila, Teerasak Punvichai, Nitipong Songtongkaew, et al. (2025) Optimization of Biojet Fuel Production From Palm Kernel Fatty Acid Distillate Using Microwave-Assisted Esterification and Distillation. Suranaree J Sci Technol 32.
65. Wulandari A, Hartono DM, Dahlan AV (2024) Life cycle assessment analysis of empty fruit bunches utilization: A case study in Riau province. AIP Conference Proceedings 3215.
66. Subramaniam V, Hashim Z (2018) Charting the water footprint for Malaysian crude palm oil. J Clean Prod 178: 675-687.
67. Anak Erison AE, Yie Hua Tan, Mubarak NM, Jibrail Kansedo, Mohammad Khalid, et al. (2022) Life cycle assessment of biodiesel production by using impregnated magnetic biochar derived from waste palm kernel shell. Environ Res 214.
68. Li Y, Wang F, Fu X, Wu Y (2026) UCO provides greater carbon reduction potential than plant oils across diverse biodiesel production technologies. J Clean Prod 545.
69. Schmidt J, De Rosa M (2020) Certified palm oil reduces greenhouse gas emissions compared to non-certified. J Clean Prod 277: 124045.
70. Bunchai A, Suttinun O, Kittikun AH, Musikavong C (2017) Life cycle greenhouse gas emissions of palm oil production by wet and dry extraction processes in Thailand. Int J Life Cycle Assess 22: 1802-1814.
71. Cucchi C, Vázquez-Rowe I, Rizo Patrón A, Echeverría-Su M, Kahhat R (2024) Identifying environmental impacts linked to the production of plant-based spreads in Peru using life cycle assessment. Sustain Prod Consum 47: 384-399.
72. Gourich W, Eng-Seng Chan, Wei Zhe Ng, Aaron Anthony Obon, Kireshwen Maran, et al. (2022) Life cycle benefits of enzymatic biodiesel co-produced in palm oil mills from sludge palm oil as renewable fuel for rural electrification. Appl Energy 325.
73. Chen HT, Yu-Hsiang He, Pei-Yi Lin, Wei-Shu Huang, Kaarmukhilnilavan R Srinivasan, et al. (2025) Cradle-to-gate carbon footprint of industrial-scale fermentative production of poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) (PHBH). J Clean Prod 536.
74. Akter HA, Dwivedi P, Masum MFH, Alam A, Anderson W (2022) sDoes Intercropping Carinata with Loblolly Pine for Sustainable Aviation Fuel Production Save Carbon? A Case Study from the Southern United States. Bioenergy Res 15: 1427-1438.
75. Deshpande SR, Sunol AK, Philippidis G (2017) Status and prospects of supercritical alcohol transesterification for biodiesel production. Wiley Interdiscip Rev Energy Environ 6.
76. Subramaniam V, Loh SK, Aziz AA (2021) GHG analysis of the production of crude palm oil considering the conversion of agricultural wastes to by-products. Sustain Prod Consum 28: 1552-1564.
77. Zolkarnain N, Subramaniam V, Ghazali R (2026) Assessing the Water Footprint of Fatty Acid Production: Identifying Hotspots and Opportunities for Sustainable Management. Process Integr. Optim. Sustain. https://link.springer.com/article/10.1007/s41660-026-00724-x.
78. Thakhiew P, Kesornpun C, Wongnate T, Kiatkittipong W, Weeranoppanant N (2022) Continuous Fatty Acid Production: Comparative Technoeconomic and Life-Cycle Analysis between Subcritical Water and Lipase Methods. ACS Sustain Chem Eng 10: 14724-14734.
79. Akmalina R, Zi Wei Ng, Rendra Hakim Hafyan, Aditya Putranto, Sharif H Zein, et al. (2026) Environmental Impact Evaluation of Octane Booster Production Derived from Lignin. Waste and Biomass Valorization. https://link.springer.com/article/10.1007/s12649-026-03525-y.