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Circular economy mapping in the palm oil value chain: Towards a conceptual framework for sustainable transition

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ABSTRACT

Background: The palm oil sector has long been a major contributor to Indonesia's economy; however, it continues to face criticism for its environmental impact. The circular economy (CE) offers a transformative approach to shift the sector from a linear system to a regenerative model centered on resource recovery, waste reduction, and value retention. This study aims to systematically map CE opportunities across all phases of the palm oil value chain, including pre-production, cultivation, processing, and consumption, and to develop a conceptual framework that supports Indonesia's transition to sustainability. **Methods:** A systematic literature review was conducted using the Scopus and Web of Science databases, following the PRISMA protocol. Publications from 2017 to 2025 were analyzed thematically to identify CE opportunities, key drivers, barriers, and interconnections across the value chain. **Findings:** CE opportunities were identified in every phase of the palm oil value chain. However, integration across phases remains limited, and coordination among stakeholders and institutions has yet to become systemic or well aligned. **Conclusion:** A holistic conceptual framework that links CE opportunities across all stages of the value chain is essential to enable a sustainable transition in Indonesia's palm oil industry. **Novelty/Originality of this article:** This study presents the first comprehensive and phase-based mapping of CE practices in the palm oil sector and introduces an integrative conceptual framework that consolidates fragmented efforts into a coherent model for Indonesia's sustainable circular transition.

KEYWORDS: circular economy; Indonesia; palm oil industry; sustainable transition; value chain.

1. Introduction

The palm oil industry represents one of the most significant agricultural sectors in Indonesia, contributing substantially to the national economy, employment, and global vegetable oil supply (Rishanty et al., 2024). Indonesia, as the world's largest palm oil producer, accounts for a major portion of global exports, positioning the industry as a critical driver of socio-economic development (Gozal et al., 2024). Despite its economic significance, the palm oil industry has increasingly attracted attention due to its

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considerable environmental and social impacts (Aprilianto & Rau, 2025; Suhartono et al., 2025). These impacts include deforestation, biodiversity loss, greenhouse gas emissions, soil degradation, water pollution, and inefficient resource utilization throughout the production cycle (Acobta et al., 2025). The linear nature of conventional palm oil production, characterized by a take-make-dispose approach, has exacerbated these challenges and highlighted the urgent need for systemic transformation toward sustainability (Astutiningsih et al., 2025).

In recent years, the concept of the circular economy (CE) has emerged as a promising paradigm to address environmental degradation and resource inefficiency in industrial systems (Sarpong et al., 2025). CE emphasizes the principles of resource recovery, waste minimization, and the retention of material and energy value within production and consumption systems (Siagian et al., 2024). In the context of agriculture and agro-industrial sectors, CE frameworks promote closed-loop processes, such as the recycling of organic waste into bioenergy, the valorization of by-products, and the reintegration of nutrients into the soil (Umor et al., 2024). Applying CE principles to the palm oil sector offers the potential to simultaneously enhance environmental performance, improve economic efficiency, and support long-term sustainability.

Despite the growing interest in CE applications in agriculture, existing research on CE practices within the palm oil industry remains fragmented. Many studies have focused on specific stages of the value chain, such as waste-to-energy initiatives (Aprilianto & Rau, 2025), effluent treatment (Mutar et al., 2025), or by-product valorization (Mansur et al., 2025), without providing a comprehensive overview that integrates all phases from pre-production to consumption. For instance, research on palm oil mill effluent (POME) treatment has primarily emphasized biogas production and energy recovery (Mutar et al., 2025), while studies on empty fruit bunches (Sulin et al., 2025) and palm kernel shells (Gopalan et al., 2024) have largely focused on biochar production and biomass energy applications. Although these studies provide valuable insights into localized circular practices, they fail to present a systemic understanding of circular economy opportunities that span the entire value chain. Consequently, there is a lack of holistic frameworks that connect these individual initiatives into a coherent strategy capable of guiding Indonesia toward a sustainable circular transition in the palm oil industry.

From a theoretical perspective, the integration of CE into industrial systems can be informed by the principles of industrial ecology, the resource-based view, and sustainability transition theory. Industrial ecology emphasizes the design of industrial systems as interconnected networks in which waste from one process becomes input for another, thereby reducing environmental burdens and improving resource efficiency (Sun et al., 2025). The resource-based view highlights the strategic utilization of internal and external resources to create value, which, when combined with circular economy practices, supports sustainable competitive advantage in agro-industrial contexts (Ntoyanto-Tyatyantsi & Amadi-Echendu, 2025). Sustainability transition theory offers insights into how socio-technical systems evolve over time, highlighting the role of policy interventions, technological innovations (Sunandar et al., 2025d), and stakeholder collaboration in driving systemic transformation (Biely & Chakori, 2025; Sunandar & Indiyati, 2023). Collectively, these theoretical perspectives provide a foundation for conceptualizing CE pathways in the palm oil sector, offering both analytical and practical guidance for industry stakeholders.

Given the economic importance of the palm oil industry and the pressing need for environmental sustainability, it is essential to identify and map circular economy opportunities across all phases of the value chain. Systematic identification of these opportunities allows for the development of an integrative framework that not only addresses existing gaps but also guides policymakers, industry practitioners, and researchers toward coordinated actions. This study aims to fill this critical research gap by conducting a systematic literature review of studies published between 2017 and 2025, covering CE initiatives across pre-production, cultivation, processing, and consumption phases. By synthesizing these findings, the study aims to provide a conceptual framework that unifies fragmented circular economy efforts, highlights interconnections among different value chain phases, and offers actionable insights for achieving a sustainable transition in Indonesia's palm oil industry.

The purpose of this manuscript is therefore threefold. First, its objective to provide a comprehensive mapping of CE opportunities across the entire palm oil value chain. Second, it seeks to identify key drivers, barriers, and interconnections among CE practices in different stages of the value chain. Third, its objective to develop a conceptual framework that integrates these insights into a cohesive model to support Indonesia's sustainable circular transition. This study contributes to the literature by offering the first phase-based, holistic assessment of CE practices in the palm oil sector and proposes a framework that addresses both theoretical and practical gaps. The originality of this work lies in its systemic perspective, bridging fragmented empirical findings and theoretical constructs to guide the industry toward an inclusive and sustainable CE transformation.

2. Methods

2.1 Research design

This study adopted a qualitative research design grounded in the principles of a Systematic Literature Review (SLR) (Patel & Patel, 2019). The qualitative design was selected to enable an in depth exploration of how CE principles have been conceptualized and implemented within the palm oil industry. This approach emphasizes interpretive synthesis rather than statistical generalization (Creswell & Creswell, 2023), making it particularly appropriate for topics that remain conceptually fragmented and theoretically diverse, such as CE applications in the oil palm sector.

A qualitative design provides the flexibility to integrate insights from different disciplinary perspectives (Miles et al., 2014), including environmental management, engineering, economics, and policy studies, allowing for a comprehensive understanding of CE adoption across the entire palm oil value chain. This design aligns with the interpretivist paradigm, which focuses on meaning making and contextual understanding rather than measurement (Saunders et al., 2023). It enables the identification of recurring themes, patterns, or conceptual that contribute to the development of a unified framework for CE implementation.

Furthermore, the qualitative SLR design supports a structured synthesis process that ensures methodological rigor and transparency (Azungah, 2018; Sunandar et al., 2025a). It allows for the systematic selection, evaluation, and interpretation of peer reviewed academic literature (Hijriyah et al., 2024; Sunandar et al., 2024), providing a credible foundation for mapping key drivers, barriers, and interconnections among CE initiatives. By doing so, it addresses the research objective of bridging fragmented insights into an integrative conceptual framework for the sustainable transformation of Indonesia's palm oil industry.

2.2 Data collection

Data were collected using a SLR method guided by the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) protocol (Hijriyah et al., 2023; Sunandar et al., 2025b). The PRISMA framework was adopted to ensure transparency in identifying, screening, evaluating, and including relevant studies (Moher et al., 2009; Page et al., 2021). Two major academic databases, Web of Science and Scopus, were selected because of their extensive indexing of peer reviewed journals and their strong relevance to sustainability, CE, and environmental management research.

The literature search was performed in October 2025 using the keywords "circular economy palm oil." These terms were searched in titles, abstracts, and keywords. The year 2017 was chosen as the starting point because this was the earliest period in which publications combining both keywords appeared in these databases. This time restriction ensures the review captures contemporary developments consistent with the global emergence of the CE agenda.

The initial search yielded 421 publications: 190 from Web of Science and 231 from Scopus. After merging records, a total of 253 articles remained for full text screening (118 Scopus and 135 WoS indexed). Non English articles, book chapters, meeting abstracts, editorials, review papers, corrections, and non research documents were excluded to maintain a focus on peer reviewed original studies.

Full text eligibility screening was then conducted to determine the relevance of each article to circular economy practices in the palm oil sector. Studies that did not directly address CE themes or were limited to unrelated agricultural contexts were removed. Duplicate records between databases were also excluded. After applying all inclusion and exclusion criteria, 40 papers were retained for qualitative synthesis. The overall process followed the four main PRISMA stages, namely Identification, Screening, Eligibility, and Inclusion, as illustrated in Fig. 1. Each stage was systematically documented to ensure reproducibility.

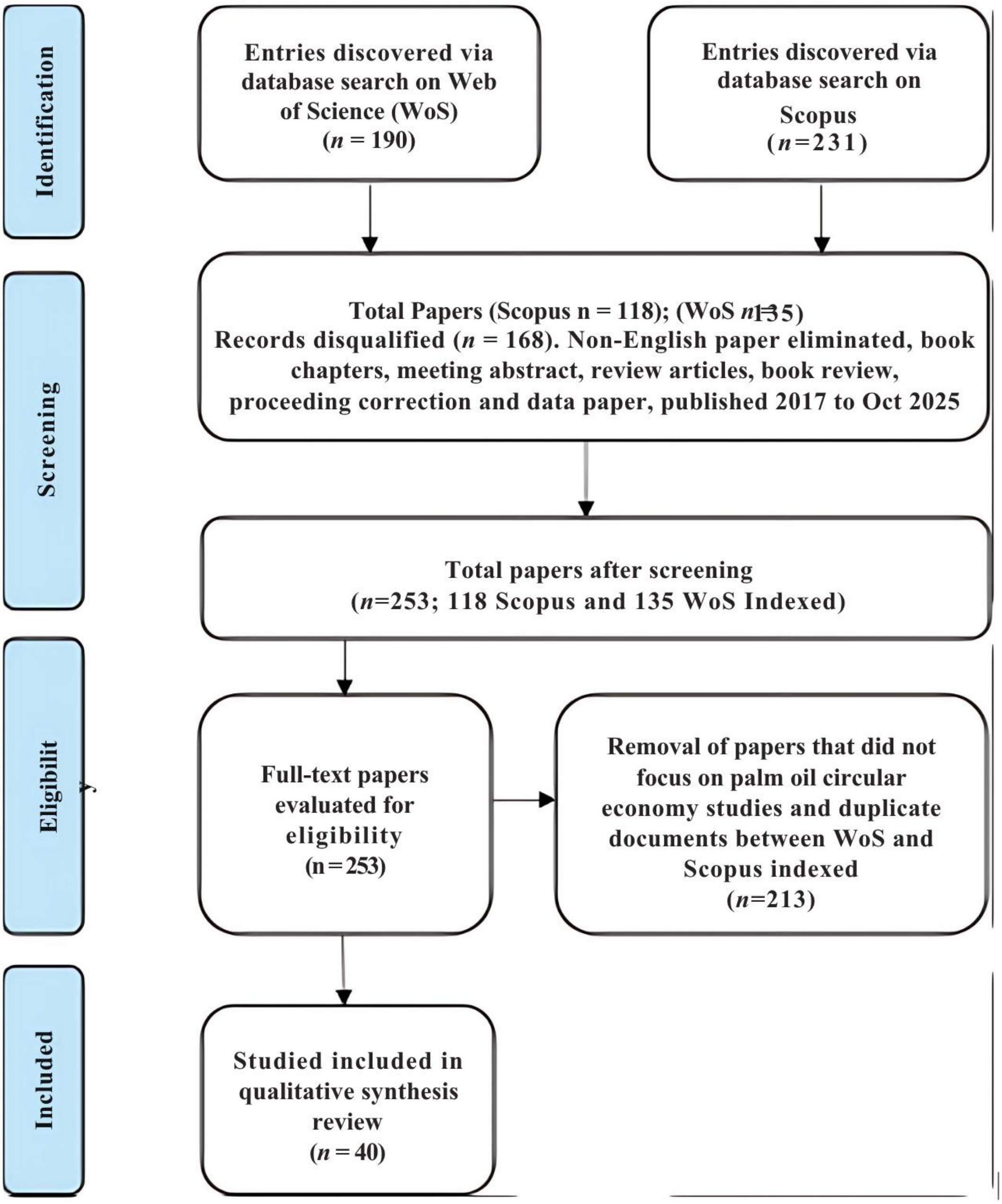

Fig. 1. The PRISMA protocol on circular economy palm oil

2.3 Data analysis

The final pool of 40 eligible papers was analyzed using thematic analysis to identify recurring themes, conceptual patterns, and emerging directions in CE research within the palm oil industry. Thematic analysis was chosen for its flexibility and capacity to extract meaning from diverse qualitative data while maintaining analytical rigor (Saldana, 2021; Sunandar et al., 2025c). It facilitates the identification of relationships among concepts, actors, and practices across different stages of the palm oil value chain, including pre production, cultivation, processing, distribution, and consumption.

The analysis was adapted using Braun and Clarke's approach, which includes familiarization with the data, generating initial codes, searching and naming for themes, and producing the final conceptual framework synthesis (Braun & Clarke, 2021). All articles were read multiple times to ensure a comprehensive understanding of context and content. Key phrases, concepts, and patterns related to circular economy opportunities, drivers, barriers, and interconnections were extracted and coded manually.

Finally, the synthesized themes were interpreted to develop a conceptual framework that maps the interconnections among circular economy practices across the palm oil lifecycle. This framework illustrates how circular economy strategies are distributed and interact across value chain phases, offering an integrated perspective to guide Indonesia's sustainable circular transition.

3. Results and Discussion

3.1 Mapping CE opportunities across the palm oil value chain

The CE represents a systemic transformation of the palm oil value chain by emphasizing resource optimization, waste valorization, and regenerative production cycles. Within the palm oil industry, which extends from land preparation to final consumption, CE provides an effective approach to reducing environmental impacts while sustaining economic competitiveness. This section maps CE practices across the palm oil value chain based on insights derived from these studies, highlighting how innovations, technologies, and management frameworks collectively contribute to the sustainable transition of the industry.

3.1.1 Pre-production phase

The pre-production phase focuses on upstream activities such as land preparation, seed selection, nursery management, and the use of inputs including fertilizers, energy, and materials. Studies emphasize the integration of renewable resources and waste-derived materials into pre-production systems to reduce dependence on virgin inputs and minimize environmental footprints. For instance, Lau et al. (2024) and Leite et al. (2022) demonstrated that compost and soil conditioners derived from palm oil waste biomass enhance soil fertility, decrease synthetic fertilizer use, and promote circular nutrient cycles. Similarly, Villa-Parejo et al. (2025) found that biochar produced from coffee and oil palm residues improves soil structure and plant growth, consistent with the CE principle of regeneration.

Furthermore, early-phase design and planning play critical roles in embedding circularity. Yeo et al. (2020) proposed a graph theoretic synthesis method to optimize resource utilization across the value chain from its initial stages, while Abdul-Hamid et al. (2021) and Ibrahim et al. (2023) highlighted the contribution of Industry 4.0 technologies to data-driven resource optimization during pre-production planning. Suprihatin et al. (2024) emphasized the adoption of circular strategies such as the reuse and recycling of agricultural inputs to prevent waste generation at the source.

Research also underscores the importance of integrating waste valorization from other sectors into palm oil pre-production. For example, Leite et al. (2022) developed a composting process using bauxite residues combined with palm mill biomass, transforming mining waste into a productive agricultural input. Similar cross-sectoral integration was explored by Sinoh et al. (2023), who examined the use of sustainable aggregates and by-products in infrastructure supporting plantation operations. Additionally, Mansur et al. (2025) and Unsomsri et al. (2025) demonstrated that biomass co-pyrolysis with plastic or mixed wastes can generate value-added products such as biofuels suitable for plantation machinery, thereby supporting energy circularity in upstream operations.

From a managerial perspective, Usapein et al. (2022) and Primadasa et al. (2025) discussed strategic frameworks including SWOT and multi-criteria decision-making to align circular planning with supply chain ambidexterity during the pre-production stage. Their findings indicate that institutional readiness and performance indicators are essential to embedding CE principles in early-stage decision-making. Collectively, these studies demonstrate that pre-production circularity encompasses not only material substitution and waste valorization but also system design, digital integration, and cross-sectoral linkages (Abdul-Hamid et al., 2022; Rajakal et al., 2023).

3.1.2 Cultivation phase

The cultivation phase, which encompasses plantation management, soil maintenance, and crop productivity, presents significant CE potential through nutrient recycling, renewable energy inputs, and emission reduction. Several studies have documented practices that reintroduce organic waste and biomass into plantation systems. Suhartono et al. (2025) demonstrated that the application of local organic waste enhances palm yield and soil health while reducing greenhouse gas emissions. Lau et al. (2024) and Villa-Parejo et al. (2025) provided complementary evidence that compost and biochar improve soil microstructure, thereby fostering carbon sequestration.

Ayompe et al. (2025) examined sustainable cultivation practices among smallholders in Cameroon, where effective waste management and recycling significantly improved resource efficiency. Poolsawad et al. (2025) developed a Material Circularity Indicator to quantify circularity performance in palm plantations, demonstrating measurable improvements in nutrient and water reuse. Similarly, Soleh et al. (2025) introduced innovative circular strategies for biomass-to-energy conversion and fertilizer recovery that can be implemented during cultivation.

Digitalization and technological innovation also play critical roles in this phase. Abdul-Hamid et al. (2021) and Lim et al. (2021) emphasized the integration of Industry 4.0 technologies such as sensor systems, the Internet of Things, and predictive analytics to monitor resource flows and enhance operational circularity. Ibrahim et al. (2023) applied fuzzy-based sustainability assessments to evaluate these technologies, revealing their potential for precision agriculture that minimizes waste.

Biochar and carbon-based materials derived from palm residues have also been explored as soil amendments. Segala et al. (2025), Morante-Carballo et al. (2024), and Gopalan et al. (2024) each confirmed the multifunctional role of biochar in improving soil fertility and capturing carbon dioxide emissions. Foong et al. (2023) discussed how microwave-assisted treatment of palm residues increases energy recovery efficiency, thereby supporting renewable energy inputs in plantation management.

Finally, studies by Bejarano et al. (2022) and Suhartini et al. (2022) reinforced the importance of anaerobic digestion of plantation waste for biogas production, which can power irrigation systems and machinery, contributing to on-site energy self-sufficiency. Collectively, these findings demonstrate that the cultivation phase represents a major leverage point for CE adoption through the recirculation of organic matter, renewable energy generation, and intelligent management systems (Ayub et al., 2021).

3.1.3 Processing phase

The processing phase represents the most intensively studied segment of the palm oil value chain in relation to CE practices. It encompasses palm oil milling, waste recovery, effluent treatment, and energy generation. Among the reviewed studies, several focus on optimizing mill operations to achieve both economic and environmental efficiency. Sulin et al. (2025) conducted a techno-economic assessment of integrated mill configurations, illustrating how waste heat recovery and material recirculation can reduce resource consumption. Tang et al. (2024) and Rishanty et al. (2024) elaborated on the valorization of POME for biogas and biofuel production, thereby reducing methane emissions while contributing to renewable energy targets.

Processing residues such as empty fruit bunches (EFB), pressed fiber, and kernel shells serve as valuable feedstocks for circular utilization. Putranto et al. (2025) investigated nanocellulose production from EFB using deep eutectic solvents, demonstrating both economic feasibility and environmental benefits. Gozal et al. (2024) examined bioethanol production from EFB, highlighting its potential for bio-based product diversification. Similar valorization pathways were explored by Castillo Santiago et al. (2025) and Mansur et al. (2025), who analyzed co-pyrolysis and co-gasification processes for producing bio-oil, syngas, and char.

The conversion of waste into functional materials also features prominently in CE research. Mustafa et al. (2025) and Morante-Carballo et al. (2024) produced activated carbon from palm residues for wastewater treatment, while Soleh et al. (2025) transformed biomass into laser-induced graphene for sensor applications, exemplifying high-value material recovery. Segala et al. (2025) found that biochar functions as an effective adsorbent for removing beta-carotene impurities during oil refining, integrating waste management with product enhancement.

Numerous studies also address energy circularity and industrial symbiosis. Rajakal et al. (2023) demonstrated that integrating palm oil processing with other industries such as food, bioenergy, and chemical manufacturing enhances circular resource exchange and reduces overall emissions. Attasophonwattana et al. (2022) proposed a multi-technology configuration combining hydrothermal carbonization, gasification, and anaerobic digestion to maximize energy recovery from EFB. Aprilianto & Rau (2025) further optimized energy generation through multi-objective models that balance efficiency with cost-effectiveness.

Emerging CE research additionally explores process digitalization and monitoring. Waudby & Zein (2021) employed simulation and techno-economic modeling to evaluate biodiesel production from POME using microwave heating, while Abdul-Hamid et al. (2022) and Foong et al. (2023) emphasized the need for integrated monitoring frameworks to achieve energy-efficient circular systems. The valorization of processing residues into carbon materials (Ayub et al., 2021; Gopalan et al., 2024) and soil amendments (Leite et al., 2022) reinforces a closed-loop connection between processing and agricultural systems.

Overall, the processing phase exhibits advanced CE maturity, as innovations extend beyond waste recovery to encompass energy symbiosis, high-value material synthesis, and process optimization enabled by Industry 4.0 technologies. These developments substantiate the palm oil sector's transition from a waste-intensive industry to a circular and low-carbon manufacturing system (Anyaoha & Zhang, 2023; Santander-Bossio et al., 2025).

3.1.4 Consumption Phase

The consumption phase represents the downstream segment of the palm oil value chain, focusing on product use, waste collection, and end-of-life management. Although it has been less extensively studied than processing, this phase is receiving increasing attention as part of CE-driven systemic transformation. Studies such as Santander-Bossio et al. (2025) highlighted community-based programs for recycling used cooking oil into biodiesel, effectively linking household waste recovery with renewable fuel production.

Similarly, Ramakanth et al. (2025) developed biodegradable smart packaging films to extend the shelf life of edible oils, thereby reducing food and material waste.

At the consumer level, initiatives promoting awareness and behavioral change have been identified as crucial enablers of circularity. Usapein et al. (2022) and Primadasa et al. (2025) emphasized performance measurement and stakeholder engagement frameworks that foster sustainable consumption patterns within supply networks. In parallel, Suksaroj et al. (2023) and Soleh et al. (2025) suggested expanding biogas and biofuel distribution to end users, thereby creating feedback loops between industrial and consumer stages.

The consumption phase also benefits from digital traceability and product transparency. Abdul-Hamid et al. (2021) proposed integrating blockchain and Internet of Things tools to track the life cycles of palm-based products, enabling efficient return and recycling systems. Bejarano et al. (2022) and Ibrahim et al. (2023) recommended using CE indicators to assess waste generation during consumption and to improve circular performance metrics.

Beyond direct product use, cross-sectoral reuse of palm-based materials demonstrates expanding consumption-stage circularity. Sinoh et al. (2023) demonstrated the potential of palm biomass residues as sustainable aggregates for the construction sector, providing new markets for downstream recycling. Similarly, Mansur et al. (2025) and Unsomsri et al. (2025) highlighted the use of co-pyrolysis fuels derived from palm and plastic wastes as substitutes for conventional energy in consumer applications.

Despite these advancements, challenges remain in scaling consumption-phase circularity, particularly in waste collection systems, product standardization, and consumer awareness. Nonetheless, the integration of policy incentives, industrial collaboration, and technological monitoring, supported by findings from Yeo et al. (2020), and Lim et al. (2021), can substantially enhance downstream circular performance.

3.1.5 Integrative summary of circular economy practices across value chain phases

The synthesis of forty studies across the four phases demonstrates that CE opportunities in the palm oil value chain extend from input optimization in pre-production to responsible end-of-life management during consumption. Each phase contributes uniquely to establishing closed loops that enhance sustainability, efficiency, and resilience within the industry. The detailed classification of CE practices is summarized in Table 1. This mapping provides a comprehensive overview of how CE principles have been operationalized across the palm oil value chain and serves as a foundation for developing an integrative conceptual framework for a sustainable transition in Indonesia.

Table 1. Circular economy practices across the palm oil value chain

Phase	Circular Economy Practice	Description
Pre-production	Compost and biochar application	Use of compost and biochar derived from palm oil waste to enhance soil fertility and reduce dependency on synthetic fertilizers.
	Industry 4.0-based planning	Application of digital monitoring, Internet of Things, and optimization tools for efficient resource allocation prior to planting.
	Waste integration from other sectors	Incorporation of bauxite, plastic, or mining residues into plantation inputs through composting and co-processing.
	Strategic circular planning	Application of SWOT and multi-criteria decision-making tools to align circular economy principles with pre-production planning.
Cultivation	Nutrient recycling and organic amendments	Reintroduction of organic waste to maintain soil health and improve yield.
	Biochar and carbon material for soil restoration	Application of biochar derived from palm residues for carbon dioxide sequestration and soil improvement.

	Renewable energy generation	Anaerobic digestion of plantation waste to produce biogas for on-site energy use.
	Digital and precision agriculture	Integration of Internet of Things, sensors, and fuzzy assessment methods for sustainability evaluation.
Processing	POME valorization and biogas production	Conversion of palm oil mill effluent into biogas and biofuel to reduce methane emissions.
	EFB valorization for nanocellulose and bioethanol	Utilization of empty fruit bunches to produce bio-based products.
	Biomass co-pyrolysis and gasification	Co-conversion of palm biomass and plastic waste into bio-oil, syngas, and char.
	Activated carbon and graphene production	Conversion of waste into high-value materials for filtration and sensor applications.
	Industrial symbiosis and energy integration	Integration across industries to reuse heat, energy, and materials.
	Process digitalization and monitoring	Application of simulation and monitoring frameworks for energy-efficient milling.
Consumption	Recycling of used cooking oil	Community-based programs converting waste oil into biodiesel.
	Biodegradable smart packaging	Development of palm-based packaging to reduce waste and extend product shelf life.
	Sustainable consumption and awareness	Stakeholder and consumer engagement to promote responsible usage.
	Blockchain and product traceability	Tracking the life cycle and recycling of palm-based products through digital tools.
	Cross-sector reuse	Utilization of palm residues in construction materials and consumer fuel applications.

3.2 Key drivers, barriers, and interconnections among CE practices

3.2.1 Key drivers of circular economy practices

The transition toward a CE within the palm oil value chain is driven by a complex interplay of technological innovation, policy enforcement, economic incentives, and sustainability imperatives. A primary driver has been the rapid advancement of waste valorization technologies that convert palm oil residues into valuable products. Research indicates that innovations in bioconversion and thermochemical processing, including pyrolysis, gasification, and hydrothermal carbonization, have substantially expanded the potential for resource recovery (Attasophonwattana et al., 2022; Mansur et al., 2025; Unsomsri et al., 2025). The production of biofuels, biochar, graphene, and nanocellulose from by-products such as EFB, POME, and palm kernel shells demonstrates how technological capabilities drive CE adoption (Ayub et al., 2021; Putranto et al., 2025; Soleh et al., 2025)

Economic and policy frameworks have also served as significant catalysts. National sustainability standards and global market pressures to comply with low-carbon and deforestation-free requirements have encouraged firms to embed CE principles into production processes (Ayompe et al., 2025; Rajakal et al., 2023). For example, regulatory initiatives in Malaysia and Indonesia that promote renewable energy generation from biomass residues have incentivized mills to invest in biogas recovery and energy optimization (Foong et al., 2023; Rishanty et al., 2024). Simultaneously, regional governments have begun integrating CE indicators into environmental impact assessments, thereby linking compliance with eligibility for export markets (Bejarano et al., 2022; Poolsawad et al., 2025).

The advancement of Industry 4.0 and digitalization has further accelerated CE adoption by enhancing traceability, process optimization, and supply chain transparency. Artificial intelligence, fuzzy-based assessment models, and multi-criteria decision-making tools enable firms to evaluate sustainability performance and identify pathways for efficient resource utilization (Abdul-Hamid et al., 2021; Ibrahim et al., 2023). The integration of automation and real-time monitoring facilitates circular manufacturing and maintenance systems that minimize losses and improve operational efficiency.

Social and environmental awareness constitutes another critical driver. Increasing recognition of the ecological degradation caused by linear palm oil production systems has motivated both corporations and communities to adopt restorative practices (Suhartono et al., 2025; Suprihatin et al., 2024). For instance, smallholders in Cameroon have implemented composting, organic fertilizer application, and waste-to-energy initiatives to enhance yields while reducing emissions (Ayompe et al., 2025). Academic collaboration and transnational research partnerships have also facilitated the diffusion of CE practices by supporting knowledge transfer and capacity building (Primadasa et al., 2025; Yeo et al., 2020). Collectively, these drivers demonstrate that the transition to CE in palm oil systems represents not merely a technological shift but also a socio-institutional transformation grounded in sustainability-oriented governance, market mechanisms, and innovation networks.

3.2.2 Financial and infrastructural barriers

Despite evident momentum, numerous barriers continue to hinder the widespread adoption of CE practices in the palm oil sector. A fundamental constraint lies in the financial and infrastructural limitations faced by small and medium enterprises as well as smallholders. The high upfront investment required for biogas facilities, pyrolysis units, and advanced filtration systems remains prohibitive in regions where access to credit and institutional support is limited (Anyaoha & Zhang, 2023; Tang et al., 2024). Economic feasibility is further constrained by volatile commodity prices and the uncertain payback periods associated with new CE technologies (Aprilianto & Rau, 2025; Sulin et al., 2025).

Technical barriers persist, particularly regarding the variability in biomass feedstock quality and the absence of standardized processing systems. The diversity of raw materials, ranging from POME and EFB to oil sludge and palm kernel shells, necessitates customized treatment methods, which complicate scaling and integration (Castillo Santiago et al., 2025; Suhartini et al., 2022). Insufficient infrastructure for collection, segregation, and logistics further impedes the closed-loop movement of materials across the value chain (Lau et al., 2024). These challenges are compounded by inadequate data sharing and limited interoperability between industrial actors.

Institutional and regulatory inconsistencies constitute another critical barrier. The absence of a harmonized CE framework across Southeast Asian countries results in fragmented implementation and monitoring. Although countries such as Malaysia and Thailand have developed material circularity indicators and pilot CE strategies, enforcement mechanisms and inter-ministerial coordination often remain weak (Poolsawad et al., 2025; Usapein et al., 2022). Policy gaps related to waste ownership, bioenergy feed-in tariffs, and carbon pricing further disincentivize private sector participation.

Socio-cultural and behavioral constraints also impede CE mainstreaming. Limited awareness among smallholders regarding the economic benefits of waste reutilization, combined with risk aversion and low technical literacy, restricts behavioral change (Ayompe et al., 2025; Suhartono et al., 2025). Resistance to technology adoption can stem from perceived disruptions to traditional practices and fear of increased operational complexity. Moreover, inadequate academic-industry collaboration and limited access to applied research outputs delay the translation of CE research into practical implementation (Morante-Carballo et al., 2024; Rajakal et al., 2023). Collectively, these interlocking barriers highlight that technological advancement alone is insufficient without comprehensive institutional reform, targeted financial incentives, and community empowerment.

3.2.3 Key drivers of CE practices

The diverse CE practices observed across the palm oil value chain are highly interdependent, forming an integrated system in which the output of one process becomes the input of another. For example, waste-to-energy and waste-to-material pathways often coexist within the same production ecosystem, enabling synergistic resource flows. Biogas recovery from POME can provide renewable energy to power pyrolysis units that produce biochar or graphene, creating a cascading effect of energy and material efficiency (Ayub et al., 2021; Foong et al., 2023). Similarly, biochar derived from pressed palm fiber or compost produced from EFB not only enriches soil fertility but also enhances carbon sequestration, thereby linking agricultural productivity with emissions mitigation (Segala et al., 2025; Villa-Parejo et al., 2025).

Digital and analytical tools have further strengthened these interconnections by enabling integrated decision-making and system optimization. Multi-criteria decision methods, graph-theoretic synthesis, and material circularity indicators are increasingly employed to model closed-loop interactions across supply chains (Yeo et al., 2020) (Primadasa et al., 2025). Such approaches reveal the mutual reinforcement among resource efficiency, energy recovery, and environmental compliance, promoting a systemic rather than linear understanding of sustainability.

Interconnections also manifest in the policy and institutional domains, where CE initiatives align with broader sustainability agendas, including climate mitigation, energy transition, and rural development. The valorization of palm residues into bioenergy directly contributes to national renewable energy targets and emission reduction commitments (Aprilianto & Rau, 2025; Rishanty et al., 2024). Furthermore, CE-oriented business models foster partnerships among mills, downstream industries, and local communities, enabling shared value creation and inclusive growth (Ayompe et al., 2025; Suprihatin et al., 2024).

The integration of industrial symbiosis across multiple sectors, such as the utilization of palm residues for construction materials, packaging films, or soil conditioners, illustrates the extensive connectivity of CE systems (Leite et al., 2022; Ramakanth et al., 2025; Sinoh et al., 2023). These cross-sectoral linkages enhance circularity by extending material life cycles beyond conventional agro-industrial boundaries. As technological, policy, and social dimensions interact, they reinforce one another in shaping a multi-layered CE network that supports Indonesia's sustainable transition. The cumulative evidence from forty SLRs underscores that achieving systemic circularity requires coordinated strategies that address both micro-level operational efficiencies and macro-level governance coherence.

3.2.4 Synthesis of drivers, barriers, and interconnections of circular economy practices

To provide a comprehensive understanding of the factors shaping CE adoption within the palm oil value chain, Table 2 presents a synthesis of the key drivers, barriers, and interconnections identified from forty SLRs. The table highlights how technological innovations, policy incentives, Industry 4.0 integration, and social awareness serve as primary drivers, facilitating the conversion of palm oil residues into biofuels, biochar, and other value-added products. At the same time, it identifies the persistent barriers, including financial limitations, technical challenges, institutional fragmentation, and socio-cultural constraints, which continue to impede CE implementation. In addition, the table emphasizes the interconnections among CE practices, such as process integration, cross-sectoral linkages, policy and governance alignment, and analytical tools, which collectively promote cascading resource flows, industrial symbiosis, and systemic sustainability. By consolidating these elements into a single framework, Table 2 offers a holistic perspective of the dynamics influencing CE transitions in the palm oil sector and provides a practical reference for policymakers, industry stakeholders, and researchers.

Table 2. Key drivers, barriers, and interconnections in circular economy practices within the palm oil value chain

CE Aspect	Elements	Implications / Examples
Drivers	Technological innovation	Pyrolysis, gasification, hydrothermal carbonization, biochar, graphene, biofuels
	Policy & economic incentives	Sustainability standards, renewable energy regulations, low-carbon compliance
	Industry 4.0 / digitalization	AI, multi-criteria decision-making, traceability, real-time monitoring
	Social & environmental awareness	Smallholder initiatives, academic collaboration, knowledge transfer
Barriers	Financial & infrastructural	High investment costs, limited credit access
	Technical	Biomass variability, lack of standard processes, logistics issues
	Institutional & regulatory	Fragmented frameworks, weak enforcement, policy gaps
	Socio-cultural & behavioral	Low awareness, risk aversion, resistance to technology, limited research translation
Interconnections	Process integration	Waste-to-energy, cascading flows, biogas powering pyrolysis units
	Cross-sectoral linkages	Biochar, compost, construction materials, packaging films
	Policy & governance alignment	Renewable energy targets, emission reductions, inclusive growth
	Analytical & digital tools	Graph-theoretic models, material circularity indicators, multi-criteria optimization

3.3 Development of an integrated conceptual framework for indonesia's circular transition

Building on the detailed mapping of CE opportunities across the palm oil value chain and the synthesis of key drivers, barriers, and interconnections, this section develops an integrated conceptual framework for Indonesia's transition toward a sustainable and circular palm oil system. This framework reflects the understanding that CE implementation is not merely a series of isolated interventions but represents a systemic transformation driven by technological innovation, policy and economic incentives, Industry 4.0-enabled digitalization, social and environmental awareness, and institutional support mechanisms.

The pre-production phase is identified as a foundational stage in the framework, in which circular strategies such as the application of compost and biochar, the integration of waste from other sectors, and digitalized planning optimize resource utilization before cultivation begins. These strategies not only reduce dependency on virgin inputs but also establish regenerative nutrient cycles that enhance soil fertility and contribute to broader sustainability objectives.

The cultivation phase, encompassing plantation management, nutrient recycling, renewable energy generation, and precision agriculture, is conceptualized as a critical leverage point for circularity. Through the recirculation of organic matter, biochar-based soil amendments, and anaerobic digestion for biogas production, this phase demonstrates how operational practices can simultaneously improve productivity, mitigate emissions, and strengthen energy self-sufficiency.

Processing represents the most intensively interconnected segment of the framework, encompassing both technological innovations and industrial symbiosis opportunities. By valorizing palm oil mill residues, including POME, EFB, and kernel shells, into biofuels, nanocellulose, biochar, activated carbon, and graphene, mills contribute to cascading material flows and high-value resource recovery. Energy integration and process optimization enabled by Industry 4.0 further enhance efficiency while reducing waste and emissions. These technological processes are closely linked with upstream and downstream activities, as recovered materials are reintegrated into agricultural systems or repurposed for industrial applications, illustrating a closed-loop system that underpins the conceptual framework.

The consumption phase extends circularity into downstream activities, including the recycling of used cooking oil, the development of biodegradable packaging, product traceability via digital platforms, and cross-sectoral reuse of palm residues in construction and energy applications. By embedding consumer engagement, awareness campaigns, and performance monitoring, this stage reinforces feedback loops connecting industrial production, household consumption, and waste management, thereby promoting systemic sustainability across the value chain.

The integrated conceptual framework also explicitly incorporates the interactions between drivers, barriers, and interconnections. Technological innovation, policy incentives, digital tools, and social awareness operate as primary drivers, enabling residue valorization and the implementation of circular practices. Persistent barriers, including financial constraints, technical challenges, institutional fragmentation, and socio-cultural resistance, are recognized as critical obstacles that must be addressed through targeted policy measures, financial mechanisms, capacity-building initiatives, and stakeholder engagement. The framework further emphasizes the interconnections among CE practices, including process integration, cross-sectoral linkages, governance alignment, and analytical tools, which collectively support cascading resource flows, industrial symbiosis, and systemic sustainability.

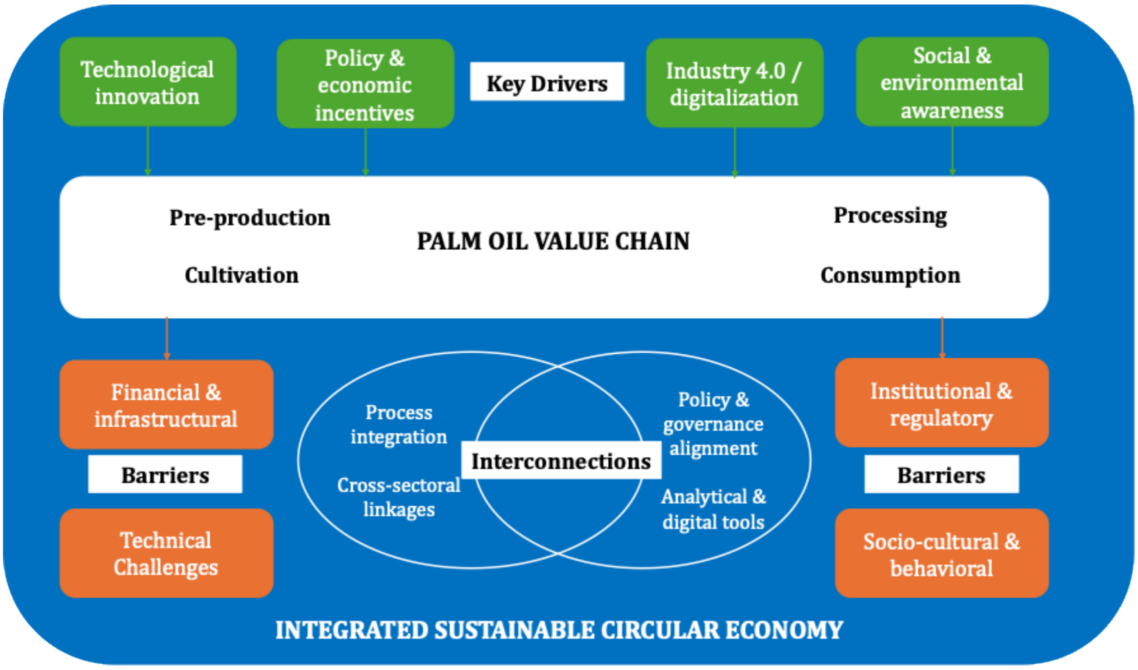

Fig. 2. Conceptual framework for the integrated circular economy transition toward sustainability in the palm oil sector in Indonesia

By integrating insights across all value chain stages, this conceptual framework (see Fig. 2) provides a comprehensive, multi-dimensional perspective on Indonesia's circular transition in the palm oil sector. It highlights the importance of aligning micro-level operational interventions with macro-level governance and policy strategies, offering a practical guide for policymakers, industry practitioners, and researchers to design, implement, and evaluate circular economy initiatives. Ultimately, this conceptualization underscores that achieving systemic circularity in Indonesia's palm oil industry requires coordinated actions across technological, institutional, social, and environmental domains, supported by evidence-based monitoring, adaptive management, and continuous innovation.

4. Conclusions

This study provides the first comprehensive and phase-based mapping of CE practices across Indonesia's palm oil value chain and develops an integrative conceptual framework that consolidates previously fragmented initiatives into a cohesive model for a sustainable circular transition. By systematically synthesizing evidence from the pre-production, cultivation, processing, and consumption phases, this research shows that circularity is only attainable when material flows, energy cycles, and socio-technical systems are intentionally designed to retain value and minimize waste throughout the entire life cycle of palm oil production. Although various CE initiatives such as biomass utilization, biogas generation, and residue valorization have been implemented, they remain scattered, uneven in technological maturity, and insufficiently integrated into national sustainability strategies. The proposed framework addresses these gaps by aligning environmental, economic, and institutional dimensions while emphasizing collaborative governance among producers, processors, policymakers, and local communities.

Beyond mapping, this study advances scientific knowledge by presenting a holistic conceptual framework that connects CE practices with key drivers, barriers, and interdependencies across all phases of the value chain. The framework positions the CE not as a continuation of waste management, but as a transformative development pathway informed by industrial ecology, sustainability transition theory, and resource-based perspectives. It highlights that systemic circularity in the palm oil sector can only be achieved when micro-level technological innovations are aligned with macro-level policy coherence, digital infrastructure, financial mechanisms, and stakeholder participation. The model serves as a practical reference for policymakers, industry practitioners, and researchers in designing, monitoring, and evaluating circular interventions that align with national sustainability targets and global climate commitments.

Despite these contributions, the study has several limitations. The analysis is primarily conceptual and based on secondary data, without quantitative assessment of material flows, economic feasibility, or social impacts. Future research should incorporate life cycle assessment or system dynamics modeling to quantify the environmental and economic benefits of CE practices across the entire value chain. Empirical studies involving smallholder farmers, local governments, and industry stakeholders are needed to assess the framework's applicability in real-world settings. Comparative studies with other palm oil-producing countries such as Malaysia, Thailand, and Colombia would also provide transferable insights and strengthen Indonesia's position in global sustainable palm oil initiatives.

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Author Contribution

The authors jointly contributed to all components of this study, including conceptualization, methodology, data collection, formal analysis, drafting of the original manuscript, review and editing, visualization, and project administration.

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Ethical Review Board Statement

Not available. This study is conceptual in nature and relies on secondary data and document reviews that are publicly accessible. It does not involve human participants, animals, or matters related to public health or safety.

Informed Consent Statement

Not available. This study did not involve human participants.

Data Availability Statement

Data supporting the findings of this study were obtained from publicly available secondary sources cited within the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the author used Grammarly to assist in improving the grammar, clarity, and academic tone of the manuscript. After using this tool, the author carefully reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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