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Barriers and opportunities of blockchain implementation for the circular economy in palm oil: A review

Abstract

As digital technologies become more embedded in sustainability-oriented supply chains, blockchain has emerged in the literature as a viable facilitator of circular economy–related practices, particularly in resource-intensive agricultural sectors such as palm oil. Despite growing scholarly attention, existing studies remain fragmented in explaining the conditions under which blockchain can effectively support the implementation of the circular economy in palm oil supply chains. This study aims to systematically identify and synthesize the key barriers and opportunities associated with blockchain adoption for circular economy applications in the palm oil sector, as documented in recent peer-reviewed research. The study is conducted using a Systematic Literature Review (SLR) design, supported by a transparent and reproducible screening protocol. Scientific articles were retrieved exclusively from the Scopus database using a structured keyword strategy. From an initial pool of 830 records, a series of inclusion and exclusion criteria, covering thematic relevance, publication period (2021–2025), language, and open-access status, yielded a final sample of 29 peer-reviewed articles. The analysis employed thematic synthesis to reveal recurrent themes and dominant analytical constructs across the included studies. The findings reveal five central themes: blockchain-enabled traceability and transparency, technological and infrastructural readiness, governance and regulatory alignment, economic feasibility, and stakeholder engagement and capacity building. The review indicates that blockchain offers significant opportunities to enhance traceability, resource efficiency, and coordination in palm oil supply chains, while adoption is constrained by infrastructural limitations, cost considerations, governance uncertainty, and human capacity gaps. In conclusion, blockchain functions as a context-dependent enabler rather than a standalone solution for implementing the circular economy. Future research is encouraged to pursue longitudinal and comparative studies that assess real-world impacts, governance models, and inclusive adoption strategies across diverse palm oil supply chain contexts.

Keywords: blockchain, circular economy, palm oil, supply chain sustainability, systematic literature review

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Introduction

The transition toward a circular economy has become an increasingly prominent agenda in global sustainability discourse, particularly in sectors characterized by complex value chains and intensive resource utilization. The circular economy framework emphasizes reducing waste, optimizing resource efficiency, and extending product life cycles through strategies such as reuse, recycling, and regeneration.[1] In contrast to the extract–use–dispose logic of linear production, circular systems prioritize strategies that keep materials and resources circulating within economic processes for as long as practicable, thereby supporting environmental sustainability while enhancing economic resilience.[2] As a result, circular economy principles have been progressively integrated into policy frameworks, corporate strategies, and technological innovation agendas across diverse industries.

Within this broader context, digital technologies have been widely recognized as key enablers of the implementation of the circular economy. The literature identifies big data analytics, the Internet of Things (IoT), artificial intelligence, and blockchain as key technologies for enhancing information flows, supervising material movements, and facilitating coordination among supply chain actors.[3] Among these technologies, blockchain has attracted particular attention due to its decentralized architecture, immutability of records, and potential to enhance trust and transparency in multi-actor systems.[4] These characteristics are particularly relevant to supply chains that involve numerous stakeholders, heterogeneous production practices, and geographically dispersed operations.

Blockchain technology is a distributed ledger system in which transactions are securely and transparently recorded in a tamper-resistant manner without centralized control. In sustainability-oriented applications, blockchain has been associated with improvements in traceability, data integrity, and accountability, which are critical components of circular economy practices. Existing studies suggest that blockchain can support more efficient tracking of material flows, facilitate verification of sustainability claims, and enable data-driven decision-making across supply chains. Consequently, blockchain has increasingly been positioned as a technological infrastructure capable of supporting circular economy objectives at both organizational and system levels.[5]

The agricultural and agri-food sectors have emerged as important domains for the application of blockchain-enabled circular economy solutions. These sectors are characterized by biological production processes, seasonal variability, and intricate networks of producers, processors, distributors, and regulators.[6] Digital traceability systems, supported by blockchain, are often discussed as mechanisms to enhance supply chain transparency, reduce inefficiencies, and support sustainable resource management in agricultural value chains. In this literature, the palm oil sector has attracted attention for its economic significance and extensive, multifaceted supply chain.[7]

The strategic relevance of palm oil in global agricultural markets is reflected in its widespread use across the food, cosmetics, energy, and industrial sectors. A broad spectrum of actors, including smallholders and large-scale enterprises, is involved in the sector, which operates throughout multiple stages of production, processing, and distribution. The inherent complexity of the sector creates both opportunities and obstacles to adopting digital technologies for sustainability and circular economy objectives. As such, the palm oil sector provides a relevant context for examining how blockchain technology is conceptualized and evaluated as a tool for enhancing the implementation of the circular economy within complex agricultural supply chains.[8]

Despite the growing body of literature addressing blockchain, circular economy, and sustainable supply chains, existing research remains fragmented across disciplinary boundaries. Many studies focus on blockchain applications in isolation, whereas others examine circular economy principles without explicitly considering the technological infrastructure required for their implementation.[9] Moreover, while several studies discuss blockchain-enabled traceability in agricultural or agri-food contexts, fewer studies explicitly integrate blockchain adoption with circular economy objectives in the palm oil sector.[10] This fragmentation limits the ability to derive coherent insights regarding the conditions under which blockchain can effectively support circular economy practices.

Another notable gap in the literature relates to the uneven treatment of opportunities and barriers associated with blockchain implementation. While optimistic narratives often emphasize the potential benefits of blockchain for transparency, efficiency, and sustainability, other studies highlight practical challenges, including technological readiness, governance complexity, cost considerations, and stakeholder capacity.[11] However, these barriers and opportunities are frequently discussed in isolation or within specific case contexts, making it difficult to identify overarching patterns and trends across the literature.[12,13] A systematic synthesis is therefore needed to consolidate existing knowledge and provide a balanced understanding of both enabling factors and constraints.

Furthermore, the rapid evolution of blockchain technologies and sustainability frameworks necessitates an up-to-date review of recent academic contributions. Advances in blockchain architectures, such as permissioned and consortium-based systems, as well as evolving interpretations of circular economy practices, have significantly influenced scholarly discussions in recent years.[14] Consequently, reviews that do not account for recent developments may overlook important shifts in research focus and methodological approaches. Addressing this issue requires a structured and transparent review process that captures contemporary scholarship while maintaining methodological rigor.[15]

In response to these gaps, Systematic Literature Review (SLR) methods have become increasingly prominent as a means of synthesizing complex and interdisciplinary research domains. SLR enables the transparent identification, selection, and analysis of relevant studies based on predefined criteria, thereby enhancing the reliability and replicability of research findings. In the context of blockchain and circular economy research, SLR offers a suitable approach for mapping thematic patterns, identifying dominant research streams, and highlighting areas requiring further investigation. Importantly, this study employs an SLR design that relies entirely on secondary data from peer-reviewed publications and does not involve primary data collection, including interviews, focus group discussions, or on-site observations.

Building on the adopted methodology, a Systematic Literature Review was conducted to analyze the barriers and opportunities associated with implementing blockchain for circular economy practices in the palm oil sector. By synthesizing peer-reviewed studies retrieved from a leading academic database, this review aims to provide a structured overview of how blockchain technology is discussed, evaluated, and positioned within the context of circular economy-oriented palm oil supply chains. Rather than advancing new empirical claims, the study focuses on consolidating existing evidence to clarify prevailing trends, recurring challenges, and emerging opportunities reported in the literature.

The specific objective of this study is to systematically identify and synthesize the key barriers and opportunities related to blockchain adoption that support the implementation of the circular economy in the palm oil sector, as documented in recent peer-reviewed research. Through a thematic analysis of selected studies, the review seeks to enhance conceptual clarity and provide an evidence-based foundation for subsequent theoretical discussion and policy-relevant interpretation.

In pursuit of this objective, the study is directed by the research questions outlined below:

RQ1: *What types of barriers to blockchain implementation for circular economy practices in the palm oil sector are most frequently identified in the existing literature?*

RQ2: *What opportunities and enabling factors are highlighted in the literature regarding the use of blockchain to support circular economy objectives within palm oil supply chains?*

These research questions structure the subsequent analysis and serve as a basis for discussion and synthesis in the later sections of the article, ensuring coherence between the review objectives, analytical findings, and concluding insights.

Literature review

The growing emphasis on sustainable production and resource efficiency has positioned the circular economy and digital innovation as central themes in contemporary supply chain research. In parallel, blockchain technology has gained increasing attention as a potential enabler of transparency, traceability, and coordination in complex, multi-actor systems. Existing literature spans diverse sectors and analytical perspectives, yet findings remain fragmented, particularly regarding how blockchain supports circular-economy objectives for resource-intensive agricultural commodities such as palm oil. This literature review synthesizes prior studies to establish a coherent conceptual foundation, examining the evolution of circular economy principles, the role of digital technologies, and the specific opportunities and barriers associated with blockchain implementation in palm oil supply chains.

Circular economy as a strategic paradigm in resource-intensive industries

The circular economy (CE) has emerged as a dominant sustainability paradigm, aimed at decoupling economic growth from resource depletion, through principles such as resource efficiency, waste minimization, recycling, reuse, and material regeneration. Unlike linear production models, circular economy frameworks emphasize closed-loop systems that extend product life cycles and optimize value retention across supply chains.[16] In resource-intensive industries, including agriculture and agro-processing, circular economy strategies are increasingly viewed as essential mechanisms for improving environmental performance while maintaining economic viability. Within agricultural systems, the implementation of the circular economy often involves optimizing biomass utilization, valorizing by-products, enhancing traceability, and reducing post-harvest losses.[17] These principles are particularly relevant for globally integrated commodity supply chains, in which production processes span multiple actors and geographic regions, creating complexity in material flows and in sustainability governance. Consequently, the literature increasingly highlights the need for digital technologies to support transparency, coordination, and accountability in circular economy transitions.

Digital technologies as enablers of circular economy transitions

Across a wide range of sectors, digitalization has been identified in the literature as a fundamental mechanism for implementing circular economy practices. Improved monitoring of resource flows, enhanced decision-making, and more efficient coordination among supply chain actors have been associated with the use of technologies such as IoT, big data analytics, artificial intelligence, and blockchain. In the context of the circular economy, digital technologies facilitate real-time data collection, lifecycle tracking, and performance measurement, thereby supporting more informed sustainability strategies.[18] Among these technologies, blockchain has attracted increasing scholarly attention due to its decentralized architecture, immutability, and capacity to enhance trust in multi-actor systems. The literature suggests that blockchain can address key coordination challenges inherent in circular economy systems, particularly in supply chains characterized by information asymmetry and fragmented governance structures.[19] In light of this, blockchain has been positioned as a foundational infrastructure capable of supporting circular economy objectives through improved traceability, transparency, and data integrity.

Blockchain technology and its relevance to sustainable supply chains

Blockchain represents a decentralized ledger system that facilitates secure, transparent, and tamper-resistant transaction recording without centralized governance.[20] From a supply chain perspective, blockchain enables shared access to verified data among stakeholders, thereby reducing information silos and transaction costs. The literature emphasizes that these features are particularly valuable in sustainability-oriented supply chains, where verification of environmental and social practices is critical. In the context of the circular economy, blockchain has been associated with capabilities such as tracking material provenance, verifying recycling processes, monitoring compliance with sustainability standards, and facilitating incentive mechanisms for circular practices. Several studies argue that blockchain can enhance the credibility of sustainability claims by providing auditable records of production and processing activities.[21] Consequently, blockchain is increasingly framed not merely as a technological innovation but as an institutional tool that supports trust-based governance in complex supply chains.

Circular economy and blockchain in agricultural and agro-industrial supply chains

The implementation of blockchain for circular-economy applications has been documented extensively in the literature on agricultural and agro-industrial supply chains, where traceability and transparency are critical. Agricultural supply chains often involve numerous smallholders, intermediaries, processors, and distributors, resulting in fragmented information flows and limited visibility across stages.[22] To address these challenges, blockchain-based platforms have been proposed to ensure end-to-end traceability and verifiable information exchange. Within the circular economy discourse, blockchain has been linked to improved management of agricultural residues, by-product valorization, and waste reduction strategies. Studies highlight that blockchain can support circular practices by documenting the transformation of agricultural waste into value-added products, thereby enhancing accountability and stakeholder confidence. This function is particularly relevant in commodity-based agricultural systems, where sustainability performance is increasingly scrutinized by regulators, investors, and consumers.[23]

The palm oil sector within the circular economy discourse

Globally, palm oil is a key agricultural commodity due to its economic significance and broad use in food production, cosmetics, bioenergy, and industrial manufacturing.[24] Due to its large-scale production and complex supply chain structure, the palm oil sector has been frequently discussed in sustainability and circular economy literature. However, existing studies emphasize that the sector also presents substantial opportunities for implementing the circular economy, particularly through biomass utilization, waste valorization, and efficiency improvements.[25] Evidence suggests that residues such as empty fruit bunches, palm kernel shells, and palm oil mill effluent can be effectively integrated into circular economy processes, thereby contributing to energy production, bio-based material production, and nutrient cycle enhancement. The literature increasingly frames the palm oil sector as a context in which circular economy strategies can enhance both environmental performance and economic resilience when supported by appropriate governance mechanisms.[26] In this regard, digital technologies, including blockchain, are viewed as tools that can strengthen coordination and transparency across palm oil supply chains.

Opportunities of blockchain for the circular economy in palm oil supply chains

The literature identifies several opportunities associated with blockchain implementation for circular economy practices in palm oil supply chains. One major opportunity lies in enhanced traceability, which enables stakeholders to track material flows from plantation to end products. Such traceability supports circular economy objectives by facilitating monitoring of resource use, waste management, and by-product utilization.[27] Another opportunity highlighted in the literature is the improvement of trust and data credibility among supply chain actors.[28] Blockchain-based systems provide immutable records that can reduce disputes and enhance confidence in sustainability-related information, which is critical to circular-economy governance. Additionally, some studies suggest that blockchain can support incentive mechanisms by linking verified circular practices to economic rewards, thereby encouraging adoption among producers and processors.[29]

Barriers to blockchain implementation in circular palm oil systems

Despite its potential, the literature also identifies significant barriers to the implementation of blockchain in circular economy contexts. Technical challenges, namely scalability constraints, data interoperability issues, and integration with existing information systems, are often cited. These challenges can be particularly pronounced in agricultural supply chains characterized by heterogeneous actors and varying levels of technological readiness.[30]

Institutional and organizational barriers are also prominent in the literature. Studies note that limited digital literacy, high initial investment costs, and uncertainty regarding return on investment can constrain blockchain adoption.[31] In addition, governance-related challenges, including data ownership, standardization, and regulatory alignment, have been identified as critical obstacles to effective implementation. In the palm oil sector, these barriers are often compounded by supply chain complexity and the involvement of multiple small-scale actors.[32]

Although a growing body of literature examines the applications of blockchain and the circular economy in agricultural supply chains, several gaps remain. First, existing studies often focus on either blockchain technology or circular economy principles in isolation, with limited integration of both perspectives. Second, empirical evidence specific to palm oil supply chains remains fragmented, with many studies adopting conceptual or exploratory approaches.

Moreover, the literature reveals an imbalance between discussions of technological opportunities and systematic analysis of implementation barriers. Few studies comprehensively synthesize both dimensions within a unified analytical framework. This fragmentation highlights the need for systematic literature reviews that consolidate existing knowledge and provide structured insights into barriers and the potential opportunities that blockchain implementation offers for circular economy activities in the palm oil sector. To bridge these gaps, the present study presents a systematic literature review that synthesizes existing research on blockchain implementation for circular economy strategies in palm oil production and supply chains. By systematically analyzing peer-reviewed literature, this review aims to integrate fragmented findings, identify recurring themes, and critically assess both enabling factors and constraints. Unlike empirical studies, this review does not generate primary data; instead, it consolidates and interprets existing evidence. A conceptual foundation is established through this approach, supporting the analysis of barriers and opportunities and presenting a comprehensive understanding of how blockchain technology has been addressed within circular palm oil systems. This synthesis advances scholarly discourse and supports evidence-based decision-making regarding sustainable supply chain innovation.

Methodology

This study employed a Systematic Literature Review (SLR) approach structured in accordance with the PRISMA protocol to ensure transparency, reproducibility, and methodological rigor. The review process was designed to identify, screen, and synthesize peer-reviewed studies that examine the application of blockchain technology to support circular economy principles, particularly in the palm oil and agricultural supply chain contexts. The SLR framework comprised four sequential stages: identification, screening, eligibility assessment, and inclusion, guided by predefined criteria related to database selection, keyword development, publication timeframe, language restrictions, and open-access availability. All procedures were conducted according to a standardized protocol that covered search strategy formulation, article selection, data extraction, and thematic organization. This section emphasizes the operational execution of the review process rather than conceptual or theoretical elaboration on blockchain or circular economy models.

Figure 1 depicts the four-stage PRISMA-guided workflow used in this review, encompassing identification, screening, eligibility assessment, and final inclusion of studies. The literature search was conducted exclusively through the Scopus database to ensure comprehensive coverage of high-quality, peer-reviewed publications across the domains of sustainability, supply chain management, and digital technology. In the identification phase, the initial keyword search for "blockchain AND circular economy" yielded 830 records. To enhance thematic precision and relevance to blockchain-enabled circular economy applications in the palm oil context, a more focused Boolean string was applied: *("blockchain" OR "distributed ledger") AND ("circular economy" OR "sustainability" OR "resource efficiency") AND ("palm oil" OR "oil palm" OR "agricultural supply chain")*. This refinement excluded 753 articles that did not align with the review's scope, leaving 77 for further consideration.

During the screening stage, a publication-year filter was applied to capture recent scholarly developments, restricting the dataset to studies published between 2021 and 2025. This step led to the exclusion of three articles, resulting in 74 remaining records. The eligibility phase then introduced a language criterion, which removed one non-English publication, yielding 73 English-language articles. A final accessibility filter was subsequently applied to include only studies available in Open Access or Open Archive formats, ensuring full-text availability for systematic analysis. At this stage, 44 articles were excluded due to limited access, producing a final corpus of 29 peer-reviewed studies that met all inclusion criteria. To maintain accuracy, avoid repetition, and ensure transparency, all references were curated and managed using Mendeley Desktop throughout the literature review. In line with the SLR methodology, this research draws exclusively on secondary data from peer-reviewed publications, without incorporating primary data collection techniques such as interviews, focus groups, or field observations. The resulting methodological foundation provides a fully replicable and auditable basis for synthesizing existing evidence on the barriers and opportunities associated with blockchain implementation for advancing circular economy initiatives within the palm oil industry.

Results

A systematic review and thematic synthesis were conducted of 29 peer-reviewed articles published between 2021 and 2025, retrieved from the Scopus database using a structured screening protocol. This study identifies five dominant and interrelated thematic clusters concerning the implementation of blockchain technology to support circular economy practices in the palm oil sector and closely related agricultural supply chains. The identified themes include: (1) Blockchain-enabled traceability and transparency across palm oil value chains, (2) Technological and infrastructural readiness as a determinant of adoption, (3) Governance, regulatory alignment, and institutional coordination, (4) Economic feasibility and cost–benefit considerations, and (5) Stakeholder engagement and capacity building as enabling conditions for circular economy integration.

An analysis of thematic distribution indicates that blockchain-enabled traceability and transparency are the most extensively discussed themes, appearing in approximately 76% of the reviewed studies. This is followed by technological and infrastructural readiness, which is addressed in around 66% of the literature. Themes related to stakeholder engagement and capacity building are identified in approximately 62% of the studies, whereas governance, regulatory alignment, and institutional coordination are addressed in about 59% of the reviewed articles. Economic feasibility and cost–

benefit considerations are discussed in roughly 55% of the studies. Importantly, more than half of the reviewed articles address multiple thematic clusters simultaneously, reflecting the multidimensional nature of blockchain adoption processes spanning technical, economic, organizational, and institutional domains.

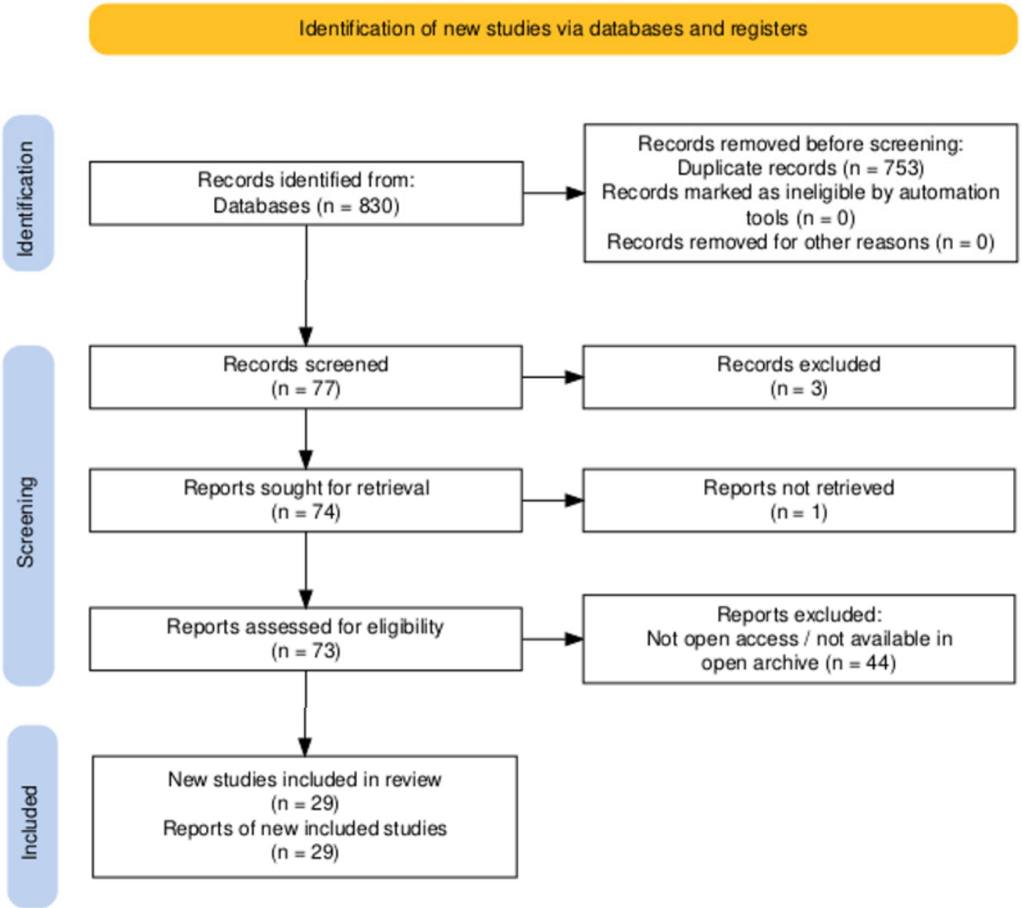

Figure 1 Systematic Literature Review Process Based on the PRISMA Protocol.

The predominance of traceability-focused studies reflects the central role of blockchain's core functionalities, immutability, distributed data storage, and shared ledger visibility in addressing long-standing challenges related to supply chain complexity and information asymmetry in palm oil production systems. Given that the implementation of the circular economy depends heavily on accurate tracking of material flows, by-product utilization, and resource efficiency, blockchain is primarily conceptualized in the literature as a foundational infrastructure for transparency rather than as a standalone sustainability solution.

The substantial emphasis on technological and infrastructural readiness highlights persistent concerns regarding implementation feasibility, particularly in contexts characterized by heterogeneous actors and uneven levels of digitalization. This focus suggests that while the potential benefits of blockchain are widely acknowledged, their realization is strongly conditioned by baseline digital infrastructure, system interoperability, and scalability. Similarly, the prominent attention given to stakeholder engagement and governance-related themes underscores growing recognition that blockchain adoption is shaped not only by technological capability but also by institutional coordination, data governance clarity, and the willingness of diverse actors to participate in shared information systems.

Collectively, these thematic patterns indicate that the literature increasingly frames blockchain implementation as a means to advance circular economy practices in the palm oil sector, emphasizing the socio-technical and institutional dimensions rather than treating it as purely a technological measure. While the capacity of blockchain to enhance transparency, coordination, and resource monitoring is well recognized, practical implementation and ecosystem-level alignment remain decisive factors. The following sections provide detailed analyses of each thematic cluster, integrating quantitative indicators and comparative evidence reported across the reviewed studies.

Blockchain-enabled traceability and transparency in palm oil value chains

Enhancing traceability and transparency in palm oil and agri-food supply chains has been identified as a central role of blockchain technology in the reviewed literature. Approximately 76% of the reviewed studies explicitly identify traceability as the primary functional contribution of blockchain systems to circular economy objectives.[33] These studies report that blockchain-based ledgers enable the immutable recording of transactions and material flows, thereby facilitating stakeholders in following palm oil products across the supply chain, from cultivation to consumption, ensuring greater traceability and reliability. Several empirical studies indicate that blockchain applications can reduce data discrepancies in supply chain reporting by 20%-40% relative to conventional centralized databases.[34]

Quantitative assessments in the literature further suggest that improved traceability contributes to more efficient resource use and waste reduction, which are central to circular economy principles. For example, studies focusing on agricultural supply chains report reductions of up to 15% in material losses when digital traceability systems are implemented alongside inventory monitoring tools.[35] In the context of palm oil, blockchain-supported traceability is frequently associated with improved monitoring of fresh fruit bunch (FFB) sourcing, certification status, and processing yields, enabling more accurate allocation of by-products and residues for downstream reuse.[36]

However, the literature also highlights that traceability gains depend on data input quality and system integration. Around 41% of studies caution that blockchain systems do not inherently guarantee data accuracy, as incorrect or incomplete inputs at early stages can propagate throughout the ledger.[37] As such, traceability improvements are most pronounced when blockchain is combined with complementary digital tools, such as Internet of Things (IoT) sensors or enterprise resource planning systems, which are reported in 38% of the reviewed articles.[38]

Technological and infrastructural readiness

Technological readiness is a critical factor influencing the feasibility of blockchain implementation in circular economy practices. Nearly two-thirds of the reviewed studies (approximately 66%) identify limitations in digital infrastructure as a significant barrier, particularly in developing-country contexts where palm oil production is concentrated.[39,40] These studies report uneven access to reliable internet connectivity, limited availability of digital hardware, and insufficient system interoperability as recurring constraints. Empirical evidence from comparative case studies indicates that blockchain pilot projects are more likely to succeed in supply chains with moderate-to-high baseline levels of digitalization. For instance, studies report adoption rates exceeding 60% among large-scale agribusiness firms with existing digital supply chain systems, compared to less than 25% among smallholder-dominated networks.[41,42] This disparity underscores the importance of foundational digital infrastructure as a prerequisite for blockchain-enabled circular economy initiatives.

From a technical perspective, scalability and energy consumption are also considered relevant. Around 34% of studies raise concerns regarding the computational intensity of certain blockchain architectures, particularly public blockchains using proof-of-work consensus mechanisms.[43] In response, several authors report a growing shift toward permissioned or consortium-based blockchains, which are reported to reduce energy consumption by up to 70% while maintaining adequate data security and transparency.[44] This trend is particularly relevant to sustainability-oriented applications in the palm oil sector.

Governance, regulatory alignment, and institutional coordination

Governance and regulatory alignment constitute another prominent theme in the reviewed literature. Approximately 59% of studies emphasize that effective blockchain implementation for circular economy outcomes depends on supportive institutional frameworks and coordinated governance arrangements.[45,46] These studies argue that unclear regulatory guidance on data ownership, digital certification, and cross-border information sharing can hinder large-scale adoption.

In the context of palm oil supply chains, governance challenges are often linked to the involvement of multiple stakeholders operating across different jurisdictions. Several studies report that fragmented regulatory environments increase transaction costs and slow decision-making processes, reducing the perceived benefits of blockchain investments.[47,48] Quantitative surveys included in the review indicate that regulatory uncertainty is cited as a major barrier by between 45% and 55% of surveyed supply chain actors.[49]

Conversely, the literature also documents instances where institutional coordination enhances blockchain adoption. Studies examining pilot initiatives supported by public–private partnerships report higher levels of stakeholder participation and compliance, with adoption rates approximately 30% higher than those of purely private-led initiatives.[50] These findings suggest that governance structures that align technological innovation with policy objectives can create more favorable conditions for integrating blockchain into circular economy strategies.

Economic feasibility and cost–benefit considerations

Economic feasibility is consistently identified as a decisive factor shaping blockchain adoption decisions. More than half of the reviewed studies (around 55%) analyze cost-related barriers, including initial investment requirements, system maintenance expenses, and integration costs.[51] Reported estimates indicate that initial blockchain implementation costs in agricultural supply chains can range from USD 50,000 to over USD 250,000, depending on system complexity and scale.[52,53]

Despite these costs, the literature also highlights potential economic benefits of blockchain-enabled circular-economy practices. Several studies report efficiency gains resulting in operational cost reductions of 10%–20% over medium-term implementation horizons.[54,55] These savings are primarily attributable to improved data management, reduced audit duplication, and enhanced coordination among supply chain actors.

Importantly, the studies reviewed emphasize that economic outcomes vary significantly with scale and stakeholder composition. Large firms and cooperatives are more likely to realize net positive returns within three to five years, while smallholders often face longer payback periods without external support.[56] As a result, economic feasibility is closely linked to financing mechanisms, cost-sharing arrangements, and policy incentives that can reduce entry barriers and more equitably distribute benefits across the value chain.

Stakeholder engagement and capacity building

Cross-cutting enablers, including stakeholder engagement and capacity building, were found to influence all other themes emerging from the review. Approximately 62% of the studies underscore the importance of human capital, organizational learning, and stakeholder collaboration in determining blockchain adoption outcomes.[57,58] These studies report that limited digital literacy and insufficient technical training can constrain effective use of systems, particularly among smallholder farmers and local intermediaries.

Quantitative evidence indicates that training and capacity-building programs can significantly improve adoption readiness. Studies report increases of 25%–40% in user acceptance rates following targeted digital training interventions.[59] Moreover, participatory implementation approaches that involve stakeholders in system design are associated with higher levels of trust and willingness to share data, which are critical for blockchain-based transparency systems.[60]

The literature also highlights the role of collaborative governance models in aligning stakeholders' incentives with circular-economy objectives. Multi-stakeholder platforms involving producers, processors, regulators, and technology providers are reported to enhance coordination and reduce resistance to change.[61] Such arrangements are particularly relevant to the palm oil sector, where supply chains are characterized by diverse actors and varying levels of capacity.

In summary, the SLR results indicate that blockchain implementation for circular economy initiatives in the palm oil industry provides significant opportunities, particularly in enhancing traceability, resource efficiency, and supply chain coordination. However, these benefits are highly dependent on technological readiness, governance support, economic feasibility, and stakeholder capacity. This thematic synthesis provides a structured empirical foundation for understanding the conditions under which blockchain can effectively contribute to circular economy practices, while also identifying areas that require further attention in future research and policy development.

Discussion

While oil palm cultivation has been associated with environmental concerns and characterized by some scholars as a driver of deforestation and an expression of agro-extractivism or agro-capitalism, empirical evidence presents a more nuanced and complex picture that warrants careful examination. Agro-extractivism refers to agricultural production systems characterized by intensive resource extraction, often for export commodities, with limited value redistribution and potential social-ecological impacts.[62,63] In the context of palm oil, critics have raised concerns that large-scale monoculture plantations create barriers to biodiversity and contribute to habitat loss in tropical regions. These concerns are legitimate and reflect real environmental challenges that the palm oil sector must address through responsible practices and certification schemes such as the Roundtable on Sustainable Palm Oil (RSPO), which has demonstrated a 33% reduction in deforestation rates compared to non-certified plantations. However, it is essential to recognize that, while responsible palm oil initiatives exist, implementation gaps persist between sustainability aspirations and observed environmental impacts on the ground.[64,65]

Empirical data indicate that the direct conversion of primary forests to oil palm plantations accounts for only a small share of total plantation establishment, challenging the perception that oil palm expansion predominantly occurs at the expense of pristine forests. Research indicates that only 32% of forest loss in Indonesia between 2001 and 2019 was ultimately converted to oil palm; 29% was cleared and converted in the same year, while a substantial portion of oil palm development has occurred on non-forest land. In Kalimantan, a comprehensive study found that over a longer period (1972-2015), industrial oil palm accounted for just 15% of total deforestation because most new plantations utilized land cleared decades earlier. Furthermore, industry data suggests that approximately 62% of oil palm plantations have been established on previously degraded land, with an additional 37% replacing agricultural areas planted with other commodities. Most critically, many oil palm plantations have been established on degraded land following timber extraction by holders of forest concession licenses.[66] In these cases, the establishment of oil palm plantations has contributed to environmental restoration by transforming abandoned, degraded land into well-managed, productive agricultural systems with enhanced carbon sequestration capacity, soil stabilization, and watershed management functions.[67] Research demonstrates that, once established, oil palm captures large amounts of carbon dioxide—approximately 64.5 tons per hectare annually—and provides superior soil protection compared with degraded or abandoned land.[68] Therefore, when developed responsibly on degraded land, with appropriate safeguards for High Conservation Value areas and adherence to no-deforestation, no-peat, no-exploitation (NDPE) commitments, oil palm cultivation can serve as a tool for landscape restoration rather than as a driver of environmental degradation.[69,70]

The findings of the systematic literature review are synthesized in this discussion to address the two research questions established in the introduction. Drawing on evidence from 29 peer-reviewed studies, the discussion critically examines the barriers and opportunities associated with blockchain implementation for promoting circular economy activities in the palm oil sector. Rather than reiterating descriptive results, this section interprets recurring patterns, compares insights across studies, and situates the findings within broader debates on digital sustainability and agri-food supply chain transformation.

Barriers to blockchain implementation for circular economy practices in the palm oil sector (RQ1)

The first research question seeks to identify the types of barriers to blockchain implementation for circular economy practices that are most frequently reported in the literature. The review reveals that barriers span technological, economic, institutional, and socio-organizational domains, which typically operate in an interconnected manner rather than in isolation. Technological barriers emerge as the most frequently cited constraint across the reviewed studies. A substantial proportion of the literature highlights limitations related to digital infrastructure, system interoperability, and scalability, particularly in production contexts characterized by heterogeneous actors and uneven levels of technological readiness.[71,72] In palm oil supply chains, where smallholders play a significant role, limited access to reliable internet connectivity and digital devices constrains the feasibility of blockchain-based systems.[73] Several studies report that while large processors and downstream actors may possess adequate digital capacity, upstream segments often lag behind, creating structural asymmetries that undermine end-to-end traceability and data continuity.[74]

Closely related to infrastructural limitations are concerns regarding data quality and system integration. The literature consistently emphasizes that blockchain does not inherently guarantee accurate or reliable data, as system integrity depends on the quality of information entered at the point of origin.[75] In agricultural contexts, manual data entry, fragmented record-keeping, and the absence of standardized data protocols are identified as significant challenges.[76] These issues are particularly salient for circular economy applications, which require precise documentation of material flows, by-product utilization, and waste management processes.[77] As a result, several authors caution against overestimating the transformative potential of blockchain without parallel investments in complementary digital tools and data governance mechanisms.

Economic barriers constitute another dominant theme in the literature. Blockchain adoption in palm oil supply chains is often hindered by high upfront costs, ongoing maintenance costs, and uncertainty about the return on investment.[78] It has been reported that the cost of establishing and operating blockchain-based traceability systems may be prohibitive for small and medium-sized stakeholders, particularly in the absence of external financial backing.[79] Moreover, the benefits of blockchain-enabled circular-economy practices are often distributed unevenly across the value chain, with upstream producers bearing a disproportionate share of implementation costs while downstream actors capture a larger share of value-added gains. This misalignment of costs and benefits is frequently cited as a deterrent to voluntary participation.

Institutional and regulatory barriers also feature prominently in the literature. A lack of clear regulatory guidance on data ownership, digital certification, and cross-border information sharing creates uncertainty that discourages long-term investment in blockchain systems.[80] When considering palm oil supply chains, which frequently span multiple jurisdictions, fragmented regulatory environments further complicate system design and governance. Several studies note that the absence of harmonized standards for blockchain-enabled sustainability reporting limits interoperability and reduces the scalability of pilot initiatives.[81] These institutional gaps are particularly problematic for circular economy applications, which rely on coordinated action across multiple stages of production, processing, and distribution.

Socio-organizational barriers, including limited digital literacy, resistance to change, and trust-related concerns, represent another recurring constraint identified in the literature. It has been widely noted that technical infrastructure alone is insufficient for blockchain adoption; it also requires human capacity and organizational preparedness. In palm oil supply chains, where producers and intermediaries vary widely in their familiarity with digital technologies, capacity gaps can impede effective use of the system and data sharing. Trust-related issues are also highlighted, as stakeholders may be reluctant to share sensitive operational data on shared platforms without clear assurances regarding data access and control.[82] These findings suggest that socio-organizational barriers are deeply intertwined with technological and institutional challenges, reinforcing the need for holistic implementation strategies.

The synthesis of the literature reveals that challenges to blockchain implementation in support of the circular economy in the palm oil sector encompass multiple dimensions and are shaped by contextual factors. Rather than reflecting inherent incompatibilities between blockchain and agricultural systems, these barriers are largely associated with structural conditions, governance arrangements, and capacity constraints that shape technology adoption outcomes.

Opportunities and enabling factors for blockchain-supported circular economy objectives (RQ2)

The second research question focuses on identifying opportunities and enabling factors highlighted in the literature on the use of blockchain to support circular-economy objectives in palm oil supply chains. In contrast to the barriers discussed above, the reviewed studies present a range of opportunities that position blockchain as a potentially valuable enabler of circular practices when implemented under appropriate conditions. Enhanced traceability and transparency constitute the most widely discussed opportunity associated with blockchain implementation. A majority of the reviewed studies emphasize that blockchain-based systems enable immutable, shared transaction records, thereby facilitating end-to-end visibility across complex supply chains.[83] In the context of the circular economy, such traceability supports more accurate monitoring of resource use, by-product flows, and waste management practices. In palm oil supply chains, blockchain-enabled traceability is frequently associated with improved documentation of fresh fruit bunch sourcing, processing yields, and residue utilization, which are critical for optimizing circular value chains.[84]

Another significant opportunity identified in the literature relates to improved governance and coordination among supply chain actors. Blockchain's decentralized architecture is often framed as a mechanism for reducing information asymmetry and enhancing trust in multi-actor systems. Several studies report that shared access to verified data can reduce transaction costs, streamline compliance processes, and facilitate collaboration across organizational boundaries. These governance benefits are particularly relevant for circular economy initiatives, which require coordinated action and shared accountability across producers, processors, and downstream stakeholders.[85]

It has been noted in the literature that blockchain holds potential in supporting incentive mechanisms for circular economy initiatives. By linking verified data on resource efficiency, waste reduction, or by-product valorization to economic or reputational rewards, blockchain-based systems can encourage participation and compliance. Some studies describe pilot initiatives in which blockchain-enabled sustainability data are used to support differentiated pricing, access to premium markets, or eligibility for policy incentives. While empirical evidence on the long-term effectiveness of such mechanisms remains limited, the literature suggests that incentive alignment is a promising avenue for promoting the adoption of the circular economy in palm oil supply chains.[86]

Technological developments and design choices are identified as important enabling factors that can mitigate some of the barriers discussed under RQ1. The reviewed studies note a growing shift toward permissioned or consortium-based blockchain architectures, which offer greater control over data access, lower energy consumption, and improved scalability compared to public blockchains. These design features are widely regarded as more suitable for sustainability-oriented applications in agricultural supply chains. Across the reviewed studies, the integration of blockchain with IoT sensors and enterprise resource planning systems is recognized as a strategy to enhance both data accuracy and system functionality.[87]

Capacity building and stakeholder engagement emerge as cross-cutting enablers across the literature. Numerous studies emphasize that training programs, participatory system design, and multi-stakeholder collaboration can significantly improve adoption readiness and system effectiveness. In palm oil supply chains, initiatives that involve producers, cooperatives, processors, and regulators in the design and governance of blockchain systems are associated with higher levels of trust and willingness to share data.[88] These findings underscore the importance of social and organizational dimensions in realizing the potential benefits of blockchain-enabled circular economy practices. Taken together, the opportunities identified in the literature suggest that blockchain can play a meaningful role in supporting circular economy objectives in the palm oil sector, particularly when implementation strategies are tailored to sector-specific conditions and aligned with broader sustainability governance frameworks.[89]

Integrative interpretation of barriers and opportunities

An important insight emerging from this SLR is that barriers and opportunities are not mutually exclusive but are often interdependent. For example, while technological limitations constrain adoption in some contexts, targeted investments in digital infrastructure and system design can transform these constraints into enabling conditions. Similarly, while governance uncertainty poses challenges, coordinated public–private initiatives can create institutional environments that support experimentation and scaling.[90] The literature thus points toward a contingent perspective on blockchain implementation, in which outcomes depend on the alignment of technological capabilities, economic incentives, institutional frameworks, and stakeholder capacities. This perspective challenges deterministic narratives that portray blockchain as either a panacea or an inherently unsuitable technology for agricultural sustainability. Instead, the findings highlight the need for context-sensitive approaches that recognize the diversity of actors and practices within palm oil supply chains.

Several research and practical implications emerge from the findings of this SLR. From a theoretical perspective, the review contributes to a more refined understanding of how digital technologies engage with circular economy principles in resource-intensive agricultural industries. By integrating insights on both barriers and opportunities, this study advances conceptual discussions on digital sustainability transitions beyond technology-centric perspectives. From a practical perspective, stakeholders pursuing blockchain adoption for the circular economy in palm oil should emphasize incremental and inclusive approaches. Investments in digital infrastructure, capacity building, and governance coordination are likely to be as important as technological design choices. Policymakers and industry actors may also consider developing supportive regulatory frameworks and incentive mechanisms to align blockchain adoption with circular-economy objectives.

This review highlights several avenues for future research. Chief among them is the need for further empirical investigations into the sustained impacts of blockchain-driven circular-economy initiatives in the context of palm oil supply chains. Second, comparative research examining different governance and business models can provide insights into conditions that facilitate successful scaling. Finally, interdisciplinary studies that integrate technological, economic, and social perspectives can further enrich the understanding of digital innovation in circular agricultural systems. It can be concluded from this discussion that implementing blockchain for circular-economy practices in the palm oil sector presents both significant challenges and meaningful opportunities. The balance among these dimensions is shaped by contextual factors rather than by technological characteristics alone, underscoring the value of systematic, integrative analyses such as the present review.

Conclusion

This systematic literature review synthesizes existing scholarly evidence on the implementation of blockchain technology to support circular-economy practices in palm oil supply chains. Based on an analysis of 29 peer-reviewed studies, the findings indicate that blockchain has been consistently positioned in the literature as a digital infrastructure with the potential to enhance traceability, transparency, and coordination in complex, resource-intensive agricultural systems. However, its effectiveness in advancing circular economy objectives is strongly shaped by contextual conditions rather than by technological characteristics alone. The reviewed literature demonstrates that barriers to blockchain implementation are multidimensional and interrelated. Technological constraints, particularly uneven digital infrastructure, data interoperability challenges, and concerns regarding data quality, are frequently identified as limiting factors, especially in supply chains involving diverse actors and varying levels of digital readiness. These constraints are reinforced by economic barriers, including high initial investment costs, uncertain return on investment, and unequal distribution of costs and benefits across supply chain actors. Institutional and regulatory uncertainties, such as unclear data governance frameworks and fragmented standards, further complicate large-scale adoption, while socio-organizational factors related to digital literacy, organizational readiness, and trust continue to influence stakeholder participation and system effectiveness.

Simultaneously, the reviewed literature emphasizes the significant potential of implementing blockchain to support circular-economy objectives in the palm oil sector. Enhanced traceability and transparency emerge as the most prominent contributions, supporting more accurate monitoring of material flows, by-product utilization, and waste management processes. Blockchain-based systems are also associated with improved governance and coordination, enabling shared access to verified information and reducing information asymmetries among supply chain actors. Moreover, the integration of blockchain with complementary digital technologies and the adoption of permissioned or consortium-based architectures are widely recognized as practical enablers that improve scalability, energy efficiency, and data control in sustainability-oriented applications. An important conclusion drawn from this review is that barriers and opportunities should not be interpreted as opposing forces but as interconnected elements within a broader socio-technical system. Many constraints identified in the literature can be mitigated through investments focused on digital infrastructure, capacity building, and coordinated governance. Multi-stakeholder engagement, participatory system design, and supportive institutional frameworks consistently emerge as critical conditions for translating blockchain's technical capabilities into tangible outcomes in the circular economy.

Overall, this review confirms that blockchain implementation for circular-economy applications in the palm oil sector holds significant potential when aligned with sector-specific characteristics and sustainability governance structures. Rather than offering a universal solution, blockchain functions as an enabling tool whose contribution depends on the alignment of technological design, economic incentives, institutional arrangements, and stakeholder capacities. By consolidating fragmented findings from the literature, this study provides a structured foundation for understanding how blockchain can support circular-economy transitions in palm oil supply chains and highlights the importance of context-sensitive, integrative approaches in future research and practice.

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Conflicts of interest

The author declares there is no conflict of interest.

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