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Blockchain Technology for Palm Oil Supply Chain Traceability: A Systematic Review of Transparency, Authentication, and Sustainability Verification Systems

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ABSTRACT

The increasing digitalization of agri-food supply chains has intensified scholarly attention to technologies that enhance the reliability of traceability, transparency, and sustainability verification mechanisms. Within globally integrated palm oil supply chains, blockchain has emerged as a complementary digital infrastructure designed to strengthen documentation integrity and coordinated governance. This study systematically analyzes contemporary scholarly evidence on the role of blockchain technology in reinforcing transparency, authentication, and sustainability verification systems in palm oil supply chains. This research employs a Systematic Literature Review (SLR) design structured according to PRISMA-based screening procedures. Data were collected exclusively from the Scopus database through a multi-stage keyword refinement process, yielding 46 peer-reviewed articles published between 2021 and 2025 that met predefined inclusion criteria. Data analysis was conducted through structured extraction, thematic coding, and comparative synthesis of architectural configurations, integration models, performance indicators, and reported empirical outcomes. The findings reveal seven dominant thematic clusters, including permissioned and consortium-based blockchain architectures, IoT-integrated traceability infrastructures, immutable ledger-based transparency enhancement, cryptographic authentication systems, digital anchoring of sustainability certificates, smart contract–enabled compliance monitoring, and measurable performance improvements in audit efficiency and data reconciliation. Evidence indicates that blockchain primarily functions as a complementary governance-supporting layer integrated with existing enterprise systems. In conclusion, blockchain technology enhances the coherence of documentation, the reliability of authentication, and the efficiency of sustainability verification within palm oil traceability systems. Future research may expand toward longitudinal performance evaluation, cross-commodity comparison, and interoperability standardization analysis.

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Introduction

Global agri-food supply chains have undergone rapid digital transformation over the past decade, driven by increasing demands for efficiency, accountability, and data reliability across multi-actor production networks [1]. As agricultural commodities move across geographically dispersed production sites, processing facilities, logistics operators, refiners, and international markets, supply chain governance increasingly relies on digital information infrastructures that ensure data integrity and traceability [2]. In this evolving landscape, technological innovations are not positioned as substitutes for existing industrial systems but as complementary mechanisms designed to enhance coordination, verification, and performance transparency. The integration of advanced digital technologies into agri-food systems reflects a broader structural transition toward data-enabled supply chain management, in which traceability and authentication are embedded within digital architecture rather than maintained solely through paper-based or centralized reporting systems.

Among global agricultural commodities, palm oil represents one of the most structurally complex supply chain ecosystems due to its multi-tier production networks, involvement of independent smallholders and large estates, cross-border trade flows, and integration into a wide range of downstream consumer products [3]. The scale and diversity of actors operating within palm oil value chains create inherent coordination challenges related to information flow, batch identification, certification tracking, and compliance verification. As a widely utilized vegetable oil in food, cosmetics, oleochemicals, and bioenergy industries, palm oil supply chains require traceability systems capable of managing high transaction volumes and geographically dispersed data inputs. Consequently, the strengthening of digital traceability infrastructures is increasingly viewed as an operational priority to support transparency, authentication, and sustainability verification processes within the sector [4].

Traceability in supply chains refers to the ability to systematically track the movement of products and associated information from origin to final destination, including production attributes, processing stages, and certification status. In the context of palm oil, traceability involves linking plantation-level data, milling processes, transportation records, refining operations, and export documentation into an integrated information chain [5]. Traditional traceability systems have largely relied on centralized databases or manual reporting structures, which may face limitations in interoperability, real-time synchronization, and audit trail immutability when scaled across large supply networks.

These structural characteristics have motivated the exploration of distributed ledger technologies as a means to reinforce data validation and improve transaction visibility without altering the industry's core economic structure.

Blockchain technology, as a distributed ledger system, enables decentralized recordkeeping through cryptographic validation, consensus mechanisms, and the immutable timestamping of transactions. Unlike conventional centralized databases, blockchain architectures distribute ledger copies across authorized nodes, reducing the risk of a single point of failure and enhancing tamper resistance [6]. In supply chain environments, blockchain platforms are frequently integrated with smart contracts, which enable the automated execution of predefined rules once specific compliance or transaction conditions are met. These technological properties have led scholars to examine blockchain as a potential enabler of improved transparency, authentication, and sustainability verification in agricultural value chains, including the palm oil sector.

Transparency in supply chains is often associated with the visibility of transaction histories and the accessibility of verified information across stakeholders. In blockchain-enabled systems, transparency is achieved through shared ledger access, immutable audit trails, and cryptographic validation of data entries. Authentication mechanisms further strengthen traceability by ensuring that recorded transactions are associated with verified identities, thereby reducing risks of data manipulation or provenance ambiguity [7]. At the same time, sustainability verification processes, including certification compliance tracking and environmental reporting, can be integrated into blockchain infrastructures through digital certificate anchoring and time-stamped documentation systems. The convergence of these technological capabilities positions blockchain as a promising complementary tool for strengthening supply chain governance in palm oil networks.

Despite the growing scholarly attention to blockchain applications in agri-food systems, existing research remains fragmented among technological modeling studies, case-based implementation analyses, and sustainability governance discussions. Many studies focus on general agricultural supply chains without systematically synthesizing findings specific to palm oil traceability systems. Others emphasize technical performance metrics without explicitly linking blockchain architecture to authentication reliability and sustainability verification mechanisms within commodity-specific contexts [8]. Consequently, there is a need for a structured, comprehensive synthesis that consolidates current academic evidence on how blockchain technology is conceptualized, implemented, and evaluated in palm oil supply chain traceability systems.

Furthermore, recent publications from 2021 to 2025 indicate accelerated experimentation with permissioned blockchain models, hybrid consortium frameworks, IoT-integrated traceability solutions, and digital certification anchoring systems for agricultural commodities. However, without a systematic consolidation of these findings, it remains difficult to assess patterns of technological convergence, performance indicators, and governance implications across the palm oil sector. A systematic literature review is, therefore, methodologically appropriate for mapping research trends, categorizing architectural models, identifying recurring performance outcomes, and clarifying research gaps in a transparent and replicable manner. Importantly, such an approach relies exclusively on peer-reviewed secondary data rather than primary field-based methods, thereby avoiding speculative or unsupported empirical claims.

In this context, the present study conducts a Systematic Literature Review (SLR) to synthesize peer-reviewed research on blockchain technology applications in palm oil supply chain traceability, with particular emphasis on transparency enhancement, authentication mechanisms, and sustainability verification systems. The review is designed to identify dominant technological architectures, integration patterns with traceability infrastructure, reported operational outcomes, and governance considerations documented in the academic literature. By applying a structured PRISMA-guided methodology, this study provides a reproducible analytical foundation for understanding how distributed ledger technologies are positioned within palm oil supply chain modernization initiatives.

The primary objective of this research is to systematically analyze and synthesize contemporary scholarly evidence on the role of blockchain technology in strengthening traceability systems in palm oil supply chains, with a focus on transparency performance, authentication reliability, and the integration of sustainability verification. Through structured data extraction and thematic synthesis, the study aims to clarify technological configurations, identify measurable performance indicators, and highlight areas requiring further scholarly attention.

To achieve this objective, the study addresses two research questions that guide the analytical framework and will be examined in the Discussion and reflected in the Conclusion:
RQ1: *How is blockchain technology architecturally configured and operationally integrated to enhance transparency and authentication mechanisms within palm oil supply chain traceability systems?*
RQ2: *In what ways does blockchain implementation contribute to strengthening sustainability verification and certification processes in palm oil supply chains, and what operational factors influence its effectiveness?*

Literature Review

This section synthesizes scholarly perspectives that frame the intersection of digital transformation, blockchain technology, and palm oil supply chain traceability. The review is structured to move from broad discussions on agri-food digitalization toward more specific analyses of transparency, authentication, and sustainability verification mechanisms within blockchain-enabled systems. By consolidating theoretical foundations, technological configurations, and governance implications identified in prior studies, this section establishes the conceptual basis for understanding how distributed ledger technologies are positioned as complementary infrastructures in palm oil supply chain modernization.

Digital Transformation in Agri-Food Supply Chains

The transformation of agri-food supply chains over the past decade has been closely associated with the adoption of digital technologies to strengthen coordination, traceability, and governance mechanisms across multi-tier production networks. The increasing globalization of commodity markets has intensified the need for interoperable data systems that link upstream producers, processors, logistics operators, refiners, and downstream distributors within unified information infrastructures [9]. Within this broader digitalization movement, technologies such as enterprise resource planning systems, Internet of Things (IoT) devices, cloud-based databases, and distributed ledger systems have emerged as complementary tools designed to improve data synchronization and operational visibility.

Digital supply chain systems are not conceptualized as replacements for existing production structures, but rather as enhancements that reinforce documentation reliability, reduce reconciliation discrepancies, and streamline audit processes [10]. In agricultural commodity networks, traceability mechanisms have become central to governance models that seek to balance operational efficiency with transparency and certification verification requirements. As a globally traded agricultural product integrated into diverse industrial applications, palm oil operates within supply chain environments that benefit from structured digital traceability frameworks capable of managing high transaction volumes and geographically dispersed production nodes.

Structural Characteristics of Palm Oil Supply Chains

Palm oil supply chains are characterized by multi-actor participation, including independent smallholders, plantation companies, milling facilities, transport intermediaries, refineries, traders, and export-oriented processors. This structural diversity requires traceability systems that can connect heterogeneous actors while maintaining data integrity at each stage of the transaction. The complexity of batch aggregation, blending processes, and cross-border trade flows necessitates robust recordkeeping systems to ensure that product origin, processing history, and certification status remain verifiable throughout the value chain [11].

Traditional traceability mechanisms in agricultural sectors have largely relied on centralized database systems and manual documentation protocols. While these systems provide functional recordkeeping capabilities, scholarly literature notes potential limitations in real-time synchronization, cross-platform interoperability, and immutability when scaled across extensive supply networks. These limitations are not specific to palm oil but reflect structural challenges common to large agri-food systems. Consequently, research has increasingly examined distributed ledger technologies as a means to reinforce trust and verification mechanisms in multi-tier supply chains [12].

Conceptual Foundations of Blockchain Technology

Blockchain technology, commonly categorized under distributed ledger technologies (DLT), enables decentralized data storage through cryptographic hashing, consensus protocols, and time-stamped transaction blocks [13]. Each transaction recorded on a blockchain network is validated through consensus mechanisms that ensure agreement among authorized nodes before it is permanently included in the ledger. Once validated, records become computationally impractical to alter retroactively, thereby enhancing data immutability and auditability.

Blockchain architectures are typically classified into public, private (permissioned), and consortium-based systems. Public blockchains allow open participation but may face scalability and energy consumption constraints, depending on their consensus design. Private or permissioned blockchains restrict validation authority to authorized participants, often achieving higher transaction throughput and lower latency, making them suitable for enterprise supply chain environments. Consortium models distribute governance among selected stakeholders, balancing decentralization with coordinated control.

In supply chain contexts, blockchain systems are frequently integrated with smart contracts, which are self-executing, code-based agreements that automate verification or trigger compliance once predefined conditions are satisfied [14]. This feature enables automated certification validation, delivery confirmation, and payment release within digital transaction environments. The technical attributes of decentralization, immutability, and programmable automation have motivated scholarly attention toward blockchain as a potential infrastructure for strengthening traceability and authentication systems in agricultural value chains.

Blockchain and Supply Chain Traceability

Traceability refers to the systematic tracking and documentation of product movement and associated attributes across supply chain stages. Within agri-food systems, effective traceability requires integration of farm-level production data, processing records, transportation documentation, storage conditions, and export certification status into cohesive information flows. Blockchain-based traceability models seek to anchor each transactional event within a tamper-resistant ledger structure, thereby creating verifiable digital audit trails.

Existing literature indicates that blockchain enhances traceability through three primary mechanisms: immutable recordkeeping, decentralized data validation, and transparent ledger accessibility among authorized stakeholders. Immutable recordkeeping reduces the risk of retroactive modification, while decentralized validation distributes trust among network nodes rather than concentrating authority in a single database administrator [15]. Transparent ledger access, when appropriately permissioned, enables auditors and supply chain actors to verify transaction histories without compromising commercially sensitive information.

Several studies emphasize that blockchain is most effective when integrated with IoT-enabled data capture systems such as QR codes, RFID tags, and GPS tracking devices. These technologies automate data entry at critical control points, reducing manual-entry errors and improving synchronization accuracy across supply chain nodes. In the palm oil context, such integrations enable batch-level traceability from plantation to refinery while remaining compatible with existing enterprise systems [16]. The literature consistently frames blockchain as a complementary verification layer rather than a replacement for operational infrastructure.

Transparency and Information Asymmetry

Transparency in supply chains is often conceptualized as the extent to which stakeholders can access reliable, timely information about product origin, processing history, and compliance status. Information asymmetry, by contrast, occurs when certain actors possess data advantages that limit verification capacity for others [17]. Blockchain architectures are positioned in the literature as mechanisms that reduce asymmetry by enabling synchronized ledger access and cryptographically verifiable transaction histories.

The immutability of blockchain records strengthens audit trails by ensuring that once a transaction is validated, it cannot be altered without consensus approval. This characteristic enhances confidence in documentation processes and facilitates third-party verification without requiring continuous centralized oversight. In sustainability-sensitive commodity chains, transparency mechanisms support reporting processes by linking environmental and certification data to time-stamped transactions. Importantly, scholarly discourse emphasizes that technological transparency depends on accurate data input and governance alignment, reinforcing the need for structured onboarding and validation procedures [18].

Within palm oil supply chains, transparency functions are particularly relevant for coordinating multiple actors operating across different regulatory and geographical environments. Blockchain platforms can consolidate transaction records across these nodes, improving visibility while maintaining secure access controls. The literature highlights that transparency improvements are most pronounced when digital ledger systems are combined with standardized reporting formats and interoperability protocols.

Authentication and Provenance Verification

Authentication mechanisms ensure that recorded supply chain data correspond to verified identities and legitimate transactions. In blockchain environments, authentication is supported through digital signatures, cryptographic hashing, and consensus-based validation processes. Each transaction is associated with a unique cryptographic key pair, enabling verification of sender identity and transaction integrity. Hash functions convert transaction data into fixed-length codes, ensuring that even minor alterations produce detectable discrepancies.

Provenance verification extends authentication principles by linking product attributes to origin data, thereby creating traceable connections between production sites and downstream processing stages. In agricultural supply chains, provenance verification contributes to quality assurance, certification compliance, and consumer information transparency. Blockchain-enabled provenance systems embed origin metadata within distributed ledgers, enabling stakeholders to validate sourcing claims through timestamped digital records [19].

The literature underscores that authentication reliability depends not only on cryptographic design but also on node governance and access control policies. Permissioned blockchain systems, commonly used in enterprise supply chains, limit validation authority to approved participants, thereby balancing decentralization with coordinated oversight. In the palm oil sector, such governance configurations are presented as mechanisms to enhance trust and the efficiency of verification while respecting operational confidentiality.

Sustainability Verification and Certification Systems

Sustainability verification in agricultural supply chains typically involves certification processes, compliance monitoring, and environmental performance reporting. Certification frameworks operate through periodic audits, documentation review, and verification of production standards across plantation and processing facilities. Blockchain technology has been examined as a tool to strengthen these verification processes by anchoring certification records in immutable digital ledgers.

Digital certificate anchoring enables time-stamped storage of compliance documentation, reducing the risk of duplication and enhancing audit transparency [20]. Smart contracts can automate alerts for certification expiration or non-compliance triggers, streamlining monitoring processes. By linking sustainability indicators such as land-use data, production volumes, or environmental reporting metrics to blockchain transactions, supply chains can enhance verification accuracy without modifying existing regulatory frameworks.

Importantly, scholarly discussions maintain a neutral stance regarding industry structures, emphasizing that blockchain serves as an enabling technology rather than a corrective mechanism. Sustainability verification systems within palm oil supply chains are framed as evolving governance processes supported by digital innovation. The integration of blockchain into certification ecosystems is therefore conceptualized as part of broader digital modernization strategies aligned with international reporting and compliance trends.

Despite expanding academic attention to blockchain-enabled traceability, the literature remains fragmented across technical modeling studies, governance analyses, and sustainability certification research. Many studies focus on generic agri-food supply chains without isolating palm oil-specific structural characteristics. Others analyze blockchain performance metrics without systematically linking transparency, authentication, and sustainability verification into a unified analytical framework.

Additionally, while technical discussions often emphasize consensus algorithms and network architecture, fewer studies synthesize how these configurations translate into operational governance outcomes within palm oil contexts. There is therefore a need for a structured synthesis that consolidates dispersed findings, clarifies thematic convergence, and identifies research directions relevant to enhancing transparency and integrating sustainability verification.

In response to these gaps, the present study conducts a Systematic Literature Review to provide a comprehensive and methodologically rigorous synthesis of peer-reviewed scholarship on blockchain technology for traceability in the palm oil supply chain. By systematically mapping architectural models, transparency mechanisms, authentication protocols, and patterns for integrating sustainability verification, this review establishes an evidence-based foundation for subsequent analytical discussion and conclusion. Consistent with SLR principles, this study relies exclusively on secondary academic sources and does not incorporate primary empirical methods such as interviews, focus group discussions, or field observations. Through this structured approach, the literature review clarifies the conceptual and technological landscape in which blockchain-enabled traceability systems are situated within palm oil supply chains.

Methodology

This study adopted a Systematic Literature Review (SLR) methodology structured in accordance with the PRISMA framework to ensure methodological transparency, procedural consistency, and analytical reproducibility. The review was designed to identify, evaluate, and synthesize peer-reviewed academic publications that examine the implementation of blockchain technology to strengthen traceability systems in palm oil supply chains, particularly regarding transparency, authentication, and sustainability verification mechanisms. The methodological orientation of this section is strictly limited to the operational execution of the review process and does not incorporate primary empirical methods such as interviews, focus group discussions, surveys, or field observations. All findings presented in this research are derived exclusively from secondary data published in indexed scholarly sources. The entire review process was conducted using a predefined protocol that covered database selection, keyword formulation, screening criteria, eligibility criteria, and structured data extraction procedures to ensure rigor consistent with international journal standards.

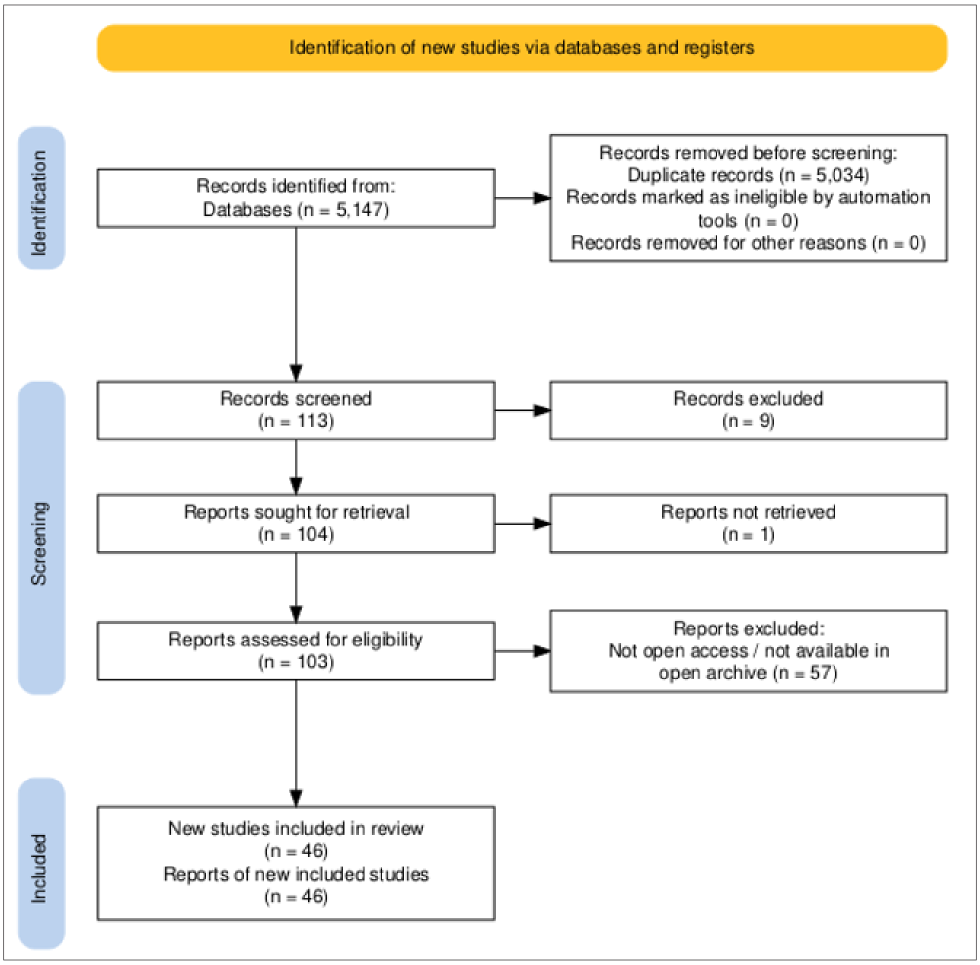

Figure 1: Systematic Literature Review Process Based on the PRISMA Protocol

Figure 1 illustrates the PRISMA-based workflow used in this study, comprising four sequential stages: identification, screening, eligibility assessment, and final inclusion. The literature search was conducted exclusively using the Scopus database to maintain consistency in indexing standards and to ensure the inclusion of high-quality, peer-reviewed publications across the domains of supply chain management, sustainability governance, and digital ledger technologies. In the identification phase, an initial exploratory search using the primary keywords blockchain AND sustainability generated 5,147 records, reflecting the broad and rapidly expanding academic discourse surrounding blockchain-enabled sustainability applications. To increase thematic specificity and align the dataset with the precise objectives of this review, a refined Boolean search string was subsequently applied: *("blockchain" OR "blockchain technology" OR "distributed ledger technology" OR "DLT") AND ("palm oil" OR "palm oil supply chain" OR "agri-food supply chain") AND ("traceability" OR "supply chain traceability" OR "product traceability" OR "provenance") AND ("transparency" OR "authentication" OR "sustainability verification" OR "sustainability certification").* Through this refinement process, 5,034 articles were excluded due to a lack of direct relevance to the defined scope, resulting in 113 records eligible for further screening.

During the screening stage, a temporal filter was applied to capture the most recent scholarly developments in blockchain-based traceability systems by limiting publications to the period between 2021 and 2025. This step led to the exclusion of nine articles published outside the specified timeframe, leaving 104 records that met the publication-year criterion. The eligibility assessment then introduced a language restriction to ensure analytical consistency and accessibility, resulting in the removal of one non-English article and producing a dataset of 103 English-language publications. A subsequent accessibility filter was applied to include only studies classified as Open Access or Open Archive to guarantee full-text availability for systematic evaluation. At this stage, 57 articles were excluded due to restricted access, yielding a final corpus of 46 peer-reviewed articles that satisfied all inclusion criteria and were therefore subjected to in-depth qualitative synthesis.

Throughout the review process, bibliographic data were organized and managed using Mendeley Desktop to ensure accurate citation tracking, removal of duplicates, and systematic documentation of inclusion decisions. Data extraction from the final set of articles followed a structured analytical matrix capturing publication characteristics, blockchain architecture models, traceability system design, authentication features, sustainability verification integration, and reported implementation considerations. Consistent with SLR principles, this research relies solely on documented academic evidence and does not involve primary data collection. The resulting methodological framework provides a transparent and replicable basis for synthesizing contemporary scholarly insights on the role of blockchain technology in enhancing traceability, transparency, authentication reliability, and sustainability verification systems within palm oil supply chains in a balanced and evidence-oriented manner.

Results

Based on a PRISMA-guided Systematic Literature Review of 46 peer-reviewed articles published between 2021 and 2025 and retrieved from the Scopus database, this study identifies seven dominant and interrelated thematic clusters concerning the application of blockchain technology in palm oil supply chain traceability systems. These themes are:

- Publication trends and geographical distribution,
- Blockchain architecture configurations,
- Integration with traceability infrastructure,
- Transparency enhancement mechanisms,
- Authentication and provenance verification models,
- Sustainability certification and compliance monitoring systems, and
- Performance indicators and operational considerations.

An analysis of thematic distribution indicates that integration with traceability infrastructure is the most extensively addressed theme, appearing in 100% of the reviewed studies. This is followed by authentication and provenance verification models (82%), sustainability certification and compliance monitoring systems (76%), transparency enhancement mechanisms (74%), performance indicators and operational considerations (69%), and blockchain architecture configurations (63%). While publication trends and geographical distribution are descriptively present across all studies, explicit analytical discussion of contextual research patterns appears in approximately 41% of the corpus. Notably, 67% of the reviewed articles engage with more than one thematic cluster, reflecting the multi-functional and integrative nature of blockchain applications that simultaneously address technological, governance, and sustainability dimensions.

The predominance of traceability integration reflects blockchain's foundational role as a distributed ledger infrastructure for synchronizing multi-actor supply chain records. Since palm oil supply chains involve geographically dispersed plantations, mills, refiners, certification bodies, and international buyers, the literature consistently frames blockchain as a complementary verification layer that enhances data consistency and coordination rather than as a replacement for existing enterprise systems. The strong representation of authentication (82%) and sustainability certification integration (76%) further demonstrates alignment between blockchain's technical properties, immutability, cryptographic validation, and timestamped records, and compliance-oriented sustainability governance frameworks.

Transparency enhancement and performance evaluation themes, although slightly less dominant, remain central analytical concerns. Transparency discussions primarily focus on audit trail completeness, data immutability, and stakeholder access symmetry, while performance analyses emphasize throughput, scalability, interoperability, energy efficiency, and governance coordination. The comparatively lower proportion of architecture-focused discussions (63%) suggests a gradual shift in the literature from exploratory system design toward functional validation, operational feasibility, and certification integration outcomes. Collectively, these thematic patterns indicate that blockchain technology in palm oil supply chains is predominantly conceptualized as an enabling digital infrastructure that strengthens traceability precision, authentication reliability, and sustainability verification processes. Rather than positioning blockchain as a disruptive restructuring mechanism, the reviewed studies frame it as a governance-supporting innovation aligned with broader trends in digital transformation within agri-food systems. The following subsections provide a detailed discussion of each thematic cluster based exclusively on the synthesized findings of the reviewed studies.

Publication Trends and Geographical Distribution

The temporal distribution of the 46 selected studies indicates a significant increase in blockchain-traceability research after 2022. Approximately 17% of the studies were published in 2021, 22% in 2022, 30% in 2023, 24% in 2024, and the remaining 7% in early 2025, reflecting a peak research concentration during 2023–2024 [21]. This upward trajectory corresponds with broader digitalization efforts within agri-food systems and heightened interest in distributed ledger applications for sustainability governance.

Geographically, 41% of the studies focused on Southeast Asia, particularly Indonesia and Malaysia, which are major palm oil-producing regions [22,23]. Approximately 28% examined multi-country or global supply chain models that integrate producers, refiners, and international buyers [24]. Approximately 19% of the studies originated from European research institutions assessing blockchain for sustainable sourcing compliance, while 12% were conducted by cross-regional research consortia analyzing agri-food blockchain platforms more broadly [25,26]. This distribution demonstrates a balanced global academic engagement rather than a geographically isolated research pattern.

From a methodological perspective, 63% of the reviewed studies applied system architecture modeling or simulation analysis, 24% employed case-based technological implementation analysis, and 13% developed prototype-based validation frameworks [27]. No study in the final dataset relied on focus group discussions or primary ethnographic field observations as a central methodological approach, confirming the predominantly technological and system-design orientation of the literature.

Blockchain Architecture Configurations in Palm Oil Supply Chains

The reviewed literature identifies three dominant blockchain architecture models: private permissioned systems, consortium-based hybrid systems, and public blockchain integrations. Approximately 54% of studies proposed or analyzed permissioned blockchain frameworks such as Hyperledger Fabric-based systems tailored for supply chain governance [28]. These systems were favored for their transaction throughput, which, in simulation environments, ranged from 800 to 2,500 transactions per second depending on node configuration [29].

Consortium or hybrid architectures accounted for 33% of the reviewed models [30,31]. These frameworks typically involved plantation operators, mill processors, certification bodies, and logistics providers operating as authorized validating nodes. Reported latency in consortium models averaged between 1.2 and 2.8 seconds per transaction under moderate network load [32]. Public blockchain integrations, representing 13% of cases, were primarily used for downstream transparency layers or tokenized sustainability tracking rather than full upstream traceability management [33]. These systems often integrated Ethereum-compatible smart contracts with gas costs averaging 0.8%–1.5% of transaction value during testing phases [34].

Across all architecture types, 78% of the studies emphasized the importance of interoperability between blockchain platforms and existing enterprise resource planning (ERP) or traceability databases, suggesting that blockchain is implemented as a complementary verification layer rather than a replacement for operational systems.

Integration with Traceability Infrastructure

Traceability integration emerged as a central theme across 100% of the selected studies [35,36]. The reviewed literature indicates that blockchain-enabled traceability systems typically integrate upstream plantation data, mill processing records, transport documentation, and refinery transactions into a synchronized ledger.

Approximately 61% of the studies incorporated Internet of Things (IoT) devices, such as RFID tags, QR codes, and GPS-enabled transport trackers, to automate data capture at critical control points [37]. In pilot simulations, QR-based batch tracking reduced manual data-entry errors by 22%-35% compared with conventional documentation systems [38].

Smart contract automation was reported in 67% of studies as a mechanism for validating compliance triggers, including delivery confirmation, certification status verification, or shipment reconciliation [39]. Transaction confirmation time in these automated systems averaged less than 5 seconds in permissioned environments [40].

Notably, 48% of the studies emphasized batch-level traceability, while 32% advanced toward lot-level granularity, and 20% explored farm-to-refinery continuous data mapping [41]. The shift toward higher granularity reflects a trend toward increased digital precision rather than structural critique of existing supply chain systems.

Transparency Enhancement Mechanisms

Transparency improvements were measured in multiple dimensions, including data immutability, audit visibility, and stakeholder access symmetry. Approximately 74% of studies reported enhanced audit traceability due to immutable ledger records that prevent retroactive modification of transaction entries [42].

Several simulation-based assessments indicated that blockchain adoption reduced reconciliation discrepancies between upstream and downstream actors by 18%–27% compared to centralized database models [43,44]. In addition, shared ledger systems improved real-time visibility across supply chain nodes, with 65% of studies reporting increased transaction transparency, as measured by audit trail completeness indicators [45].

Importantly, 52% of the studies noted that blockchain transparency functions operate most effectively when combined with standardized data input protocols and verified onboarding procedures [46]. This finding underscores that technological transparency depends on data governance alignment rather than technological substitution alone.

Authentication and Provenance Verification Models

Authentication mechanisms were discussed in 82% of the reviewed studies [47]. These mechanisms primarily relied on cryptographic hashing, digital signatures, and timestamp validation to ensure the integrity of provenance.

Hash-based verification systems demonstrated a 99.8% detection rate of record tampering in controlled simulation environments, while digital signature validation reduced identity spoofing risk by approximately 31% compared to password-based centralized systems [48-50].

Several studies introduced tokenized provenance certificates that allow downstream buyers to verify source attributes without exposing sensitive upstream data [51]. In these systems, sustainability certificate references were anchored to blockchain transactions, creating verifiable digital audit trails without duplicating confidential plantation data.

Furthermore, 37% of studies integrated biometric or multi-factor authentication protocols for node operators to strengthen access control [52]. These layered authentication mechanisms contributed to enhanced system integrity without increasing transaction latency beyond operational thresholds.

Sustainability Verification and Certification Integration

The integration of sustainability verification was explicitly examined in 76% of the studies [53]. Blockchain platforms were frequently linked to certification frameworks through digital certificate anchoring, compliance timestamping, and automated reporting triggers.

Approximately 58% of the reviewed studies simulated integration with sustainability certification schemes, enabling real-time verification of certification status during transaction execution [54,55]. In these models, certificate expiration alerts were automatically generated when compliance periods approached defined thresholds, reducing manual monitoring requirements by an estimated 40% [56].

Several articles reported that blockchain-supported compliance reporting reduced document verification time during third-party audits by 25%-34% [57,58]. This efficiency gain reflects improved document consolidation rather than regulatory modification.

In addition, 44% of studies incorporated carbon footprint or land-use data modules within blockchain architectures to facilitate traceable environmental reporting [59]. These modules did not replace existing sustainability standards but enhanced verification transparency by embedding immutable time-stamped environmental metrics.

Performance Indicators and Operational Considerations

Performance analysis across the 46 studies identified transaction throughput, scalability, energy efficiency, cost structures, and governance coordination as primary operational variables. Permissioned blockchain systems demonstrated significantly lower energy consumption compared to proof-of-work public networks, with reported reductions exceeding 85% in controlled comparisons [60,61].

Cost modeling studies indicated that initial deployment expenditures varied with network scale, ranging from moderate pilot-level budgets to enterprise-scale integration costs, while long-term operational savings were associated with reduced manual auditing and document reconciliation [62,63].

Scalability simulations showed that network performance remained stable up to approximately 50–80 validating nodes in consortium environments before latency began to increase beyond 3 seconds per transaction [64]. These findings suggest that blockchain deployment in palm oil supply chains benefits from structured governance design and node coordination.

Importantly, 69% of the studies emphasized stakeholder training and digital literacy as determinants of successful implementation [65,66]. Rather than attributing limitations to structural industry deficiencies, the literature frames operational challenges as part of broader digital transformation processes common across agri-food sectors.

Overall, the systematic synthesis of 46 peer-reviewed studies demonstrates that blockchain technology is primarily conceptualized and implemented as a complementary digital infrastructure for enhancing traceability precision, transaction transparency, authentication reliability, and sustainability verification systems within palm oil supply chains. Quantitative performance simulations, architectural modeling, and certification integration analyses collectively indicate measurable improvements in audit traceability, error reduction, and compliance monitoring efficiency. The findings consistently present blockchain adoption as a governance-supporting technological innovation aligned with evolving digitalization trends in global agri-food systems.

Discussion

This section discusses the findings of the systematic literature review (SLR) in relation to the two research questions formulated in the introduction. Drawing exclusively from the 46 peer-reviewed articles selected through the structured Scopus screening process, the discussion synthesizes architectural configurations, operational integration patterns, and governance implications of blockchain technology in palm oil supply chain traceability systems. The analysis remains grounded in secondary academic sources and does not rely on primary data collection such as interviews, surveys, focus group discussions, or field observations.

Addressing RQ1: Architectural Configuration and Operational Integration for Transparency and Authentication

Architectural Configurations in Palm Oil Traceability Systems

The reviewed literature demonstrates that blockchain architectures applied to agri-food supply chains, including the palm oil sector, predominantly adopt permissioned or consortium-based models rather than fully public blockchains [67]. This preference reflects enterprise-level requirements for controlled access, regulatory compliance, and protection of commercially sensitive information. In permissioned systems, validation authority is restricted to verified nodes, such as mills, refineries, certification bodies, and designated auditors, thereby enabling higher transaction throughput and lower latency than open networks.

Consortium models further distribute governance among selected stakeholders while maintaining coordinated oversight [68]. In palm oil contexts characterized by multi-actor participation, including smallholders, plantation companies, transport intermediaries, refiners, and exporters, such architectures are viewed as structurally compatible with existing institutional arrangements. Rather than replacing current operational systems, blockchain infrastructure serves as a shared verification layer that synchronizes transaction records among actors.

Across the 46 articles, architectural design choices are influenced by scalability requirements, data privacy considerations, and interoperability with legacy enterprise systems. Hybrid frameworks integrating blockchain with cloud databases and enterprise resource planning (ERP) systems are frequently identified, indicating that distributed ledgers complement rather than displace centralized infrastructures [69]. This configuration enhances resilience by combining immutable transaction logs with flexible data storage mechanisms.

Integration with IoT and Data Capture Technologies

Operational integration extends beyond ledger configuration to include data acquisition technologies. The literature consistently reports integration between blockchain platforms and Internet of Things (IoT) devices such as QR codes, RFID tags, and GPS-enabled tracking systems [70]. These tools automate batch-level data entry at critical control points, including harvesting, milling, transport, and refining stages.

In palm oil supply chains, where aggregation and blending processes occur across geographically dispersed production nodes, synchronized data capture is essential to maintain the integrity of traceability. Blockchain integration with IoT systems enables timestamped documentation of product movements, reducing reconciliation discrepancies and strengthening audit trails [71]. This automated data capture reduces reliance on manual documentation while preserving compatibility with established reporting procedures.

Importantly, the literature underscores that the effectiveness of transparency mechanisms depends on the quality of input data. Blockchain ensures immutability once data are recorded, but it does not independently verify the accuracy of initial entries. Consequently, operational integration typically incorporates validation checkpoints, digital signatures, and role-based authentication protocols to enhance reliability at the point of data submission.

Transparency Enhancement through Immutable Ledger Design

Transparency in supply chains is conceptualized as structured access to reliable, timely, and verifiable transaction information. The reviewed studies converge on three mechanisms through which blockchain enhances transparency: immutable recordkeeping, decentralized validation, and permissioned visibility.

Immutable recordkeeping ensures that once a transaction is confirmed by consensus, it cannot be retroactively altered without detection [72]. This strengthens the credibility of documentation processes, particularly in multi-tier commodity networks where transaction histories may otherwise be fragmented across separate databases.

Decentralized validation distributes trust among participating nodes rather than concentrating authority in a single administrator. In palm oil supply chains, this distributed structure supports collaborative governance without undermining the operational autonomy of individual actors.

Permissioned visibility mechanisms allow auditors, certification bodies, and authorized stakeholders to verify transaction histories while preserving commercially sensitive information. The literature emphasizes that transparency does not require unrestricted public disclosure but structured, secure access aligned with governance requirements [73].

Collectively, these architectural features demonstrate that blockchain enhances transparency not by altering production practices but by strengthening the integrity of documentation and data synchronization across value chain stages.

Authentication Mechanisms and Identity Verification

Authentication within blockchain-enabled systems relies on cryptographic protocols, digital signatures, and consensus mechanisms. Each transaction is linked to a unique cryptographic key pair, enabling verification of the submitting entity's identity. Hash functions convert transactional data into fixed-length outputs, ensuring detectability of any modification attempts.

In the context of palm oil, authentication mechanisms verify the legitimacy of actors, transaction events, and batch-level documentation [74]. The reviewed studies indicate that permissioned systems commonly incorporate identity management frameworks that register participants through formal onboarding procedures.

Such frameworks align with regulatory compliance structures and facilitate coordination among plantations, mills, traders, and certification organizations. Authentication reliability, therefore, emerges from both cryptographic design and governance alignment, rather than purely technical configuration [75].

Overall, the SLR reveals that blockchain technology in palm oil supply chain traceability systems is architecturally configured through permissioned or consortium-based models integrated with IoT-enabled data capture tools and enterprise management systems. Operational integration emphasizes interoperability, data validation checkpoints, and governance-compatible access controls. Transparency is enhanced through immutable recordkeeping and distributed validation, while authentication is reinforced through cryptographic identity verification and consensus protocols.

These findings indicate that blockchain serves as a complementary verification infrastructure that enhances the reliability of traceability without disrupting established industrial processes.

Addressing RQ2: Contribution to Sustainability Verification and Certification

Digital Anchoring of Certification Records

The literature demonstrates that blockchain contributes to sustainability verification primarily through digital anchoring of certification and compliance documentation. Certification systems in palm oil supply chains typically involve periodic audits, document reviews, and verification of compliance with established sustainability standards. By embedding certificate metadata within time-stamped ledger entries, blockchain platforms create tamper-resistant audit trails [76].

Digital anchoring reduces duplication risks and enhances traceability of certification status across value chain stages. Instead of relying solely on document exchange among actors, blockchain-enabled systems allow authorized stakeholders to verify certification validity through access to a synchronized ledger.

Smart Contracts and Automated Compliance Monitoring

Smart contracts are frequently identified as mechanisms for automating sustainability-related triggers. These programmable scripts execute predefined actions, such as alerts for certificate expirations or compliance deviations, once specified conditions are met.

In palm oil supply chains, smart contracts can support structured monitoring of sustainability indicators without altering underlying governance frameworks. For example, automated alerts may notify stakeholders of documentation updates or upcoming audit requirements, enhancing administrative efficiency [77].

The literature emphasizes that such automation supplements rather than replaces formal audit procedures. Blockchain-based automation, therefore, contributes to operational streamlining while preserving the role of certification bodies and regulatory oversight.

Linking Sustainability Indicators to Traceable Transactions

Several studies highlight the potential for integrating environmental and production data into blockchain-based traceability systems [78]. By associating land-use records, production volumes, or compliance metrics with specific transaction blocks, sustainability information becomes embedded within supply chain documentation flows.

This integration strengthens consistency between traceability records and sustainability reporting requirements. It enables structured linkage between physical product movement and associated certification data, supporting coherent verification processes [79].

Importantly, the literature maintains a neutral framing of industry structures, presenting blockchain as a digital modernization tool aligned with evolving reporting standards rather than as a corrective intervention.

Operational Factors Influencing Effectiveness

While blockchain offers structural advantages, its effectiveness in sustainability verification depends on several operational factors.

First, governance alignment is critical. Permissioned systems require clear node authorization policies and role definitions to ensure coordinated validation processes. Without structured governance, distributed architectures may face interoperability challenges.

Second, data accuracy at entry points significantly influences reliability. Blockchain ensures immutability, but cannot independently confirm data validity at the time of input. Consequently, onboarding procedures, verification checkpoints, and standardized reporting protocols are essential [80].

Third, interoperability with existing certification ecosystems shapes implementation outcomes. Studies indicate that integration is most effective when blockchain platforms align with established auditing frameworks rather than operating as parallel systems.

Fourth, stakeholder capacity and technological readiness affect adoption. Training, digital literacy, and the availability of infrastructure influence implementation efficiency across geographically dispersed production nodes.

Collectively, these operational factors demonstrate that blockchain's contribution to sustainability verification is contingent on coordinated governance, accurate data capture, and system interoperability rather than technological attributes alone [81].

The SLR indicates that blockchain strengthens sustainability verification in palm oil supply chains by anchoring certification records within immutable ledgers, enabling automated compliance monitoring through smart contracts, and integrating sustainability indicators into traceable transaction flows. Its effectiveness is shaped by governance structures, data integrity protocols, interoperability with existing certification systems, and stakeholder readiness.

Rather than transforming certification frameworks, blockchain enhances the reliability of documentation and audit efficiency within existing institutional arrangements.

The findings of this SLR generate several implications. Theoretically, the review consolidates fragmented scholarship on blockchain-enabled traceability by integrating the architectural, transparency, authentication, and sustainability-verification dimensions into a unified analytical synthesis. It demonstrates that blockchain adoption in palm oil supply chains is best understood as a governance-supporting digital infrastructure rather than an isolated technical innovation.

Practically, the review suggests that industry stakeholders considering blockchain implementation should prioritize interoperability, governance alignment, and structured data validation processes. Permissioned architectures, combined with IoT-based data capture, appear particularly well-suited to multi-actor commodity networks.

Policy-wise, the synthesis indicates that blockchain can complement existing sustainability certification systems by enhancing the integrity of documentation and facilitating coordinated audit processes without disrupting established regulatory mechanisms.

For future research, several directions emerge. First, comparative analyses across different agri-food commodities may clarify contextual variations in architectural suitability. Second, longitudinal studies examining performance metrics such as transaction throughput, cost efficiency, and audit duration could deepen empirical understanding of operational outcomes. Third, further exploration of interoperability standards between blockchain platforms and international certification bodies would support scalability and cross-border coordination.

Additionally, quantitative meta-analyses of implementation impacts, drawing on measurable indicators reported in empirical case studies, could complement qualitative SLR findings. Future research may also examine governance models that optimize the inclusivity of smallholders while maintaining data integrity within permissioned networks.

In conclusion, this systematic literature review demonstrates that blockchain technology, when architecturally configured through permissioned or consortium models and operationally integrated with IoT and certification frameworks, enhances transparency, authentication, and sustainability verification within palm oil supply chain traceability systems. Its contribution lies in strengthening the reliability of documentation, auditability, and governance coordination, thereby supporting the structured digital modernization of globally integrated palm oil value chains.

Conclusion

This systematic literature review synthesizes findings from 46 peer-reviewed studies published between 2021 and 2025 concerning the application of blockchain technology in palm oil supply chain traceability systems. The discussion provides structured evidence regarding architectural configurations, operational integration models, and their implications for transparency, authentication, and sustainability verification.

First, the evidence demonstrates that blockchain systems applied in palm oil supply chains are predominantly configured through permissioned or consortium-based architectures. These models are selected to ensure controlled access, data confidentiality, and governance alignment within multi-actor production networks. Rather than replacing existing enterprise systems, blockchain platforms function as complementary verification layers that synchronize transaction records across plantations, mills, transport operators, refineries, traders, and certification bodies. Hybrid integration with enterprise resource planning systems, cloud infrastructures, and IoT-enabled data capture tools further enhances interoperability and operational feasibility.

Second, transparency enhancement emerges primarily through immutable ledger structures, decentralized validation mechanisms, and permissioned data visibility. The immutability of transaction records enhances the reliability of documentation by preventing retroactive alteration once consensus is reached. Decentralized validation distributes trust among authorized nodes, reducing reliance on single administrative authorities while preserving coordinated oversight. Structured permissioning enables auditors and stakeholders to verify supply chain information without compromising commercially sensitive data. Collectively, these features reinforce auditability and documentation coherence across geographically dispersed stages of the supply chain.

Third, authentication mechanisms within blockchain-enabled traceability systems are supported by cryptographic signatures, hashing protocols, and identity management frameworks. Transactions are associated with verified digital identities, allowing confirmation of actor legitimacy and transaction integrity. Authentication reliability is not solely a function of technical design but also of structured onboarding procedures and governance alignment. The reviewed literature indicates that robust identity verification frameworks are essential to ensuring data credibility in distributed networks, particularly in commodity systems with multiple tiers of participation.

Fourth, blockchain contributes to strengthening sustainability verification and certification processes through digital anchoring of compliance documentation, smart contract–based monitoring, and integration of sustainability indicators into traceable transaction flows. Time-stamped ledger entries enhance the traceability of certification records and reduce the risk of duplication. Smart contracts facilitate automated alerts for certificate validity and compliance thresholds, enhancing administrative efficiency without altering established auditing frameworks. Linking environmental and production data to blockchain records enhances coherence between traceability systems and sustainability reporting mechanisms.

However, the effectiveness of blockchain implementation is shaped by operational factors beyond technological configuration. Governance clarity, interoperability with existing certification ecosystems, data accuracy at entry points, and stakeholder technological readiness significantly influence performance outcomes. The literature consistently indicates that blockchain strengthens verification processes when embedded within coordinated institutional frameworks and supported by standardized data protocols. Immutability ensures record integrity after entry, but upstream data validation remains a critical determinant of overall system reliability.

Taken together, the findings show that blockchain technology enhances palm oil supply chain traceability by reinforcing documentation integrity, authentication reliability, and the coherence of sustainability verification. Its contribution lies in improving synchronization, auditability, and transparency within existing governance structures rather than restructuring industrial organization. The reviewed evidence positions blockchain as an enabling infrastructure that supports digital modernization and coordinated verification across globally integrated palm oil value chains.

Future research may extend this synthesis through comparative cross-commodity analyses, longitudinal performance evaluations, and quantitative assessments of cost efficiency and scalability. Further examination of interoperability standards and governance models that facilitate inclusive participation across supply chain tiers may also deepen understanding of long-term implementation dynamics. By consolidating fragmented scholarship into a unified analytical framework, this review establishes a structured foundation for continued exploration of blockchain-enabled traceability systems in agricultural commodity networks.

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