

Supply chain visibility in palm oil under AI adoption: a review of benefits, risks, and implementation gaps

Abstract

Palm oil supply chains face increasing pressure to demonstrate verifiable, technology-supported traceability amid tightening sustainability regulations and certification requirements, yet the growing body of literature on artificial intelligence (AI) adoption in this sector remains fragmented across disciplinary and methodological boundaries. This study aims to systematically review and synthesize peer-reviewed literature examining the adoption of AI and complementary digital technologies to enhance supply chain visibility within the palm oil industry, with particular attention to the benefits reported, the risks and constraints identified, and the implementation gaps that persist across the reviewed evidence base. A Systematic Literature Review (SLR) design guided by the PRISMA protocol was employed, relying exclusively on secondary data and not involving primary data collection through interviews, focus group discussions, or field observation. Data were collected through the Scopus database using a staged keyword strategy, beginning with 166 records for “artificial intelligence AND palm oil,” refined through a more specific Boolean search to 53 records, filtered by publication year (2021–2026) to 51 records, and narrowed through relevance screening to a final set of 24 included studies. Data were analyzed through thematic synthesis across five recurring areas of focus. Results indicate that AI and blockchain adoption is consistently associated with improved data integrity, verification efficiency, and certification alignment, while implementation is constrained by infrastructure limitations, cost, digital literacy gaps, and limited smallholder inclusion. The review concludes that visibility gains depend more on organizational and institutional readiness than on technological sophistication alone. Future research is recommended to pursue cross-regional comparative studies and longitudinal evaluation of deployed systems.

Keywords: supply chain visibility; artificial intelligence; palm oil; traceability; systematic literature review

Special Issue - 2026

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Received: August 05, 2026 | **Published:** August 27, 2026

Introduction

Palm oil constitutes one of the most economically significant vegetable oil commodities in global trade, supplying a substantial share of the world's edible oil and oleochemical demand while generating considerable rural employment and foreign exchange revenue for producing economies, particularly across Southeast Asia.¹ Its exceptionally high oil yield per hectare relative to competing oilseed crops has positioned palm oil as a land-efficient source of vegetable oil, reinforcing its continued relevance to global food security and industrial supply amid rising demand from food, cosmetics, pharmaceutical, and renewable energy sectors.² As international trade in agricultural commodities becomes increasingly subject to sustainability scrutiny, downstream buyers, regulators, and consumers have progressively demanded verifiable evidence of responsible sourcing across multi-tier palm oil supply networks.³ Regulatory instruments such as the European Union Deforestation Regulation, together with voluntary and mandatory certification schemes including the Roundtable on Sustainable Palm Oil and the Indonesian Sustainable Palm Oil standard, have reinforced this expectation by requiring traceable documentation linking finished products back to their plantation of origin.^{4,5} These developments have collectively elevated supply chain visibility from an operational convenience to a strategic and, in several jurisdictions, a compliance-driven necessity for palm oil producers, processors, and exporters.

In parallel with these sustainability-driven pressures, digital transformation has reshaped supply chain management across the global agri-food sector, with artificial intelligence emerging as a particularly influential enabling technology.⁶ AI encompasses a broad set of computational techniques, including machine learning, deep

learning, computer vision, and natural language processing, that allow organizations to move from reactive to predictive and prescriptive decision-making across production, logistics, and compliance functions.^{7,8} When combined with complementary technologies such as blockchain, Internet of Things sensors, and satellite-based remote sensing, AI has demonstrated the capacity to support real-time monitoring, anomaly detection, and automated verification across complex, multi-actor supply networks in sectors ranging from manufacturing to food distribution.⁹ Within agricultural commodity systems more specifically, AI-enabled analytics have been applied to yield forecasting, land-use classification, and traceability verification, with reported outcomes indicating measurable improvements in predictive accuracy and documentation reliability relative to conventional statistical and manual approaches.

Supply chain visibility, understood as the extent to which supply chain actors share and access timely, accurate, and reliable information regarding product origin, movement, and condition, has been established in the broader operations management literature as a determinant of organizational performance and coordination capability. Prior theoretical work grounded in resource-based and organizational information-processing perspectives has identified antecedents, barriers, drivers, and performance effects associated with visibility across diverse supply chain settings, though this foundational literature has developed largely outside the specific context of tropical agricultural commodities such as palm oil.¹⁰ Within the palm oil sector specifically, visibility challenges are compounded by the structural complexity of the supply chain, which typically spans estate-owned plantations, plasma smallholders, and a substantial population of independent smallholders whose fresh fruit bunch output is frequently aggregated through informal or semi-formal channels prior

to milling. This structural fragmentation has historically limited the traceability of raw material origin, creating both a practical obstacle to certification compliance and a recurring point of emphasis in recent studies examining blockchain- and AI-enabled traceability solutions tailored to smallholder-inclusive supply chains.¹¹

Despite this growing body of technical and applied research, the existing literature on AI adoption in palm oil supply chains remains comparatively fragmented across disciplinary and methodological boundaries. A considerable proportion of published studies concentrate narrowly on the design or performance validation of individual blockchain architectures, machine learning models, or spatial information systems, generally evaluated within single-country or single-case settings rather than synthesized across the broader body of evidence. Comparable digital transformation domains, including manufacturing and general agri-food logistics, have already benefited from consolidated systematic reviews that map recognized frameworks of enabling factors, adoption barriers, and performance outcomes, yet an equivalent level of synthesis remains comparatively underdeveloped for palm oil supply chain visibility specifically.¹² Moreover, where reviews of digital technology adoption in the palm oil sector do exist, they tend to privilege either the technical benefits of specific tools or, separately, the barriers to their diffusion, rather than integrating benefits, risks, and implementation gaps within a single coherent analytical frame. This fragmentation constrains the ability of researchers, industry practitioners, and policymakers to form an evidence-based, comparative understanding of how AI adoption is reshaping visibility across the palm oil value chain as a whole, and it leaves open the question of where technological promise and practical feasibility currently diverge most sharply.¹³

Addressing this gap carries both academic and industrial urgency. Academically, a structured synthesis extends the supply chain visibility literature into a commodity context characterized by distinctive smallholder-dominated production structures and intensifying regulatory scrutiny, thereby testing the applicability of visibility frameworks developed primarily in retail and manufacturing settings. Industrially, palm oil producers, exporters, and certification bodies face mounting pressure to demonstrate verifiable, technology-supported traceability within compressed regulatory timelines, making a consolidated understanding of what AI-enabled visibility solutions can realistically deliver, and where their current limitations lie, a matter of immediate operational relevance.

This study therefore aims to systematically review and synthesize peer-reviewed literature examining the adoption of artificial intelligence and complementary digital technologies to enhance supply chain visibility within the palm oil industry, with particular attention to the benefits reported, the risks and constraints identified, and the implementation gaps that persist across the reviewed evidence base. Consistent with a Systematic Literature Review design guided by the PRISMA protocol, this study relies exclusively on secondary data drawn from peer-reviewed publications indexed in the Scopus database and does not involve primary data collection through interviews, focus group discussions, or field observation. To guide this synthesis and to frame the subsequent Discussion and Conclusion sections, the review addresses the following research question: *Under what conditions does AI adoption enhance supply chain visibility in the palm oil industry, what benefits and risks have been reported, and what implementation gaps continue to limit scalable, certification-aligned deployment?*

Literature review

Supply chain visibility has been conceptualized in the operations management literature as the extent to which supply chain partners possess timely, accurate, and useful information regarding the location, condition, and movement of goods, and, more broadly, as the capability of the network to convert dispersed data into actionable insight for decision-makers.¹⁴ Early theoretical treatments of this construct drew principally on resource-based theory, arguing that distinctive visibility functions as a firm-specific resource capable of generating sustainable competitive advantage when it is difficult for competitors to replicate.¹⁵ This resource-based framing was subsequently extended through organizational information-processing theory, which conceptualizes visibility as a mechanism for reducing uncertainty and equivocality within inter-organizational networks by matching information-processing capacity to the complexity of the coordination task at hand.¹⁶ A more recent systematic synthesis consolidated these perspectives into an integrative framework distinguishing antecedents, barriers and challenges, drivers, and effects of visibility, noting that roughly half of the empirical literature in this domain does not explicitly anchor its analysis in a named theory, which points to a degree of conceptual fragmentation even within mainstream supply chain visibility research.¹⁷ Collectively, these theoretical strands establish visibility not as a binary condition but as a graduated capability shaped jointly by technological infrastructure and inter-organizational trust, a distinction that becomes particularly salient when visibility is examined within agricultural commodity chains characterized by a high degree of actor fragmentation.¹⁸

The diffusion of artificial intelligence and complementary digital technologies into supply chain management has commonly been interpreted through innovation-diffusion and technology-organization-environment perspectives, which frame adoption as a function of perceived relative advantage, organizational readiness, and external institutional pressure.¹⁹ Within this framing, AI is understood as a class of computational techniques, including machine learning, deep learning, and natural language processing, that enable a shift from descriptive to predictive and prescriptive decision-making across production planning, logistics coordination, and compliance verification.²⁰ Empirical work applying this lens to agribusiness contexts has shown that the maturity of AI adoption typically progresses through identifiable stages, beginning with standalone predictive models and advancing toward integrated, multi-source decision-support architectures, though full-system integration linking production, environmental, and market data remains comparatively rare across the reviewed evidence.²¹ This staged view of technological maturity resonates with dynamic capability theory, which posits that the value of a given technology is realized not at the point of adoption but through an organization's capacity to sense, seize, and reconfigure resources around that technology over time.²² Read alongside resource-based and information-processing perspectives on visibility, this suggests that AI adoption and supply chain visibility are theoretically interdependent rather than parallel phenomena: AI functions as an information-processing capability that operationalizes the antecedents of visibility identified in earlier supply chain theory, while visibility in turn constitutes the observable outcome through which the value of AI adoption becomes measurable.²³

Blockchain technology occupies a distinctive theoretical position within this literature, frequently discussed less as a predictive analytical tool and more as a governance infrastructure that enforces

data immutability, decentralization, and verifiable provenance across multiple, potentially non-trusting parties.²⁴ Governance-oriented theorizing of blockchain adoption has proposed that its function varies systematically with the complexity of the underlying value chain and the intensity of governance required, yielding differentiated configurations rather than a single universal traceability model.²⁵ This variation is consistent with transaction cost economics, which suggests that blockchain reduces the cost of verifying and enforcing agreements among dispersed actors, thereby lowering the transaction costs that would otherwise constrain coordination in fragmented agricultural supply networks.²⁶ When positioned alongside AI-based predictive analytics, blockchain can therefore be understood as addressing the trust and verification dimension of visibility, while AI addresses its forecasting and pattern-recognition dimension, with the two technologies functioning as theoretically complementary rather than substitutable components of a broader digital visibility architecture.²⁷

The structural characteristics of palm oil supply chains introduce a further layer of theoretical relevance, particularly given the sector's reliance on independent smallholders who frequently operate outside formal registration, certification, or digital record-keeping systems.²⁸ Global value chain theory offers a useful lens for interpreting this structure, distinguishing between buyer-driven and producer-driven governance forms and highlighting how lead firms exert coordination influence over upstream actors through standards, certification requirements, and, increasingly, digital verification mechanisms.²⁹ Within palm oil specifically, this governance dynamic intersects with institutional theory, which explains the adoption of certification schemes such as the Roundtable on Sustainable Palm Oil and national standards including the Indonesian Sustainable Palm Oil system as a response to coercive, normative, and mimetic pressures exerted by regulators, international buyers, and industry peers respectively.³⁰ The European Union Deforestation Regulation exemplifies coercive institutional pressure in this context, translating sustainability expectations into a binding compliance requirement that explicitly depends on verifiable, plot-level traceability data. Institutional theory thus provides a bridge between the technical literature on blockchain-enabled traceability and the regulatory literature on certification compliance, suggesting that digital visibility tools are, in large part, being adopted as an institutional response mechanism rather than purely as an operational efficiency measure.³¹

Taken together, these theoretical strands converge on a central proposition relevant to the present review: supply chain visibility in palm oil under AI adoption is best understood as the intersection of three theoretical domains that have historically been examined in relative isolation from one another. Resource-based and information-processing theories explain why visibility matters and how it generates value; technology-organization-environment and dynamic capability perspectives explain how and why AI-based tools are adopted and matured within organizations; and institutional and value chain governance theories explain the external pressures, particularly certification and regulatory compliance, that shape the specific form visibility solutions take within a smallholder-dominated commodity sector.³² Prior reviews addressing digital transformation in the broader agri-food sector have tended to draw on only one or two of these theoretical strands at a time, most commonly technology adoption or institutional compliance perspectives, without integrating the resource-based and information-processing foundations of visibility theory itself.³³ This theoretical fragmentation mirrors the empirical

fragmentation noted in prior systematic reviews of the palm oil digitalization literature, in which studies addressing blockchain architecture, machine learning applications, and certification compliance are frequently published as parallel but disconnected streams of inquiry.

This synthesis therefore positions the present review as an attempt to read these theoretical strands jointly rather than separately, treating AI adoption, blockchain-based governance, and certification-driven institutional pressure as interacting mechanisms that collectively determine the depth and reliability of supply chain visibility achieved in practice. Consistent with a Systematic Literature Review design, this theoretical positioning is developed exclusively through the analysis of secondary, peer-reviewed sources rather than through primary data collection, interviews, or field-based observation, ensuring that the conceptual linkages proposed here remain grounded in the existing body of published evidence rather than in exploratory qualitative inquiry. The Results and Discussion sections that follow apply this integrated theoretical lens to interpret the benefits, risks, and implementation gaps identified across the 24 reviewed studies, with particular attention to where resource-based visibility gains, technology-organization-environment adoption patterns, and institutional compliance pressures reinforce one another and where, conversely, they appear to diverge.

Methods

This study employs a Systematic Literature Review (SLR) approach based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure transparency, consistency, and reproducibility throughout the review process. The review systematically examines peer-reviewed scientific publications related to the adoption of artificial intelligence in enhancing supply chain visibility within the palm oil industry, with particular emphasis on the benefits offered by AI-based technologies, the risks and limitations associated with their deployment, and the gaps that remain in translating these technologies into practical implementation across palm oil supply chains. This study does not involve primary data collection, focus group discussion, or field observation, and relies exclusively on previously published scientific literature. To ensure database consistency and indexing quality, the literature search was restricted to publications indexed in the Scopus database. The PRISMA protocol was applied through the stages of identification, screening, eligibility assessment, and final inclusion, enabling the systematic selection of studies that are directly relevant to the objectives of this review.

The article selection procedure employed in this study is illustrated in Figure 1. During the identification stage, an initial search was conducted within the Scopus database using the broad keyword combination *artificial intelligence AND palm oil*, which yielded 166 records. To improve the specificity and thematic relevance of the retrieved literature, the search strategy was subsequently refined using a more focused Boolean search string: *("palm oil" OR "oil palm") AND ("supply chain visibility" OR "supply chain" OR traceability OR transparency) AND ("artificial intelligence" OR AI OR "machine learning" OR "deep learning" OR "digital transformation" OR blockchain)*. Following this refinement process, 113 articles were excluded because they did not align with the thematic scope of AI-driven supply chain visibility in the palm oil sector, resulting in 53 articles for further evaluation.

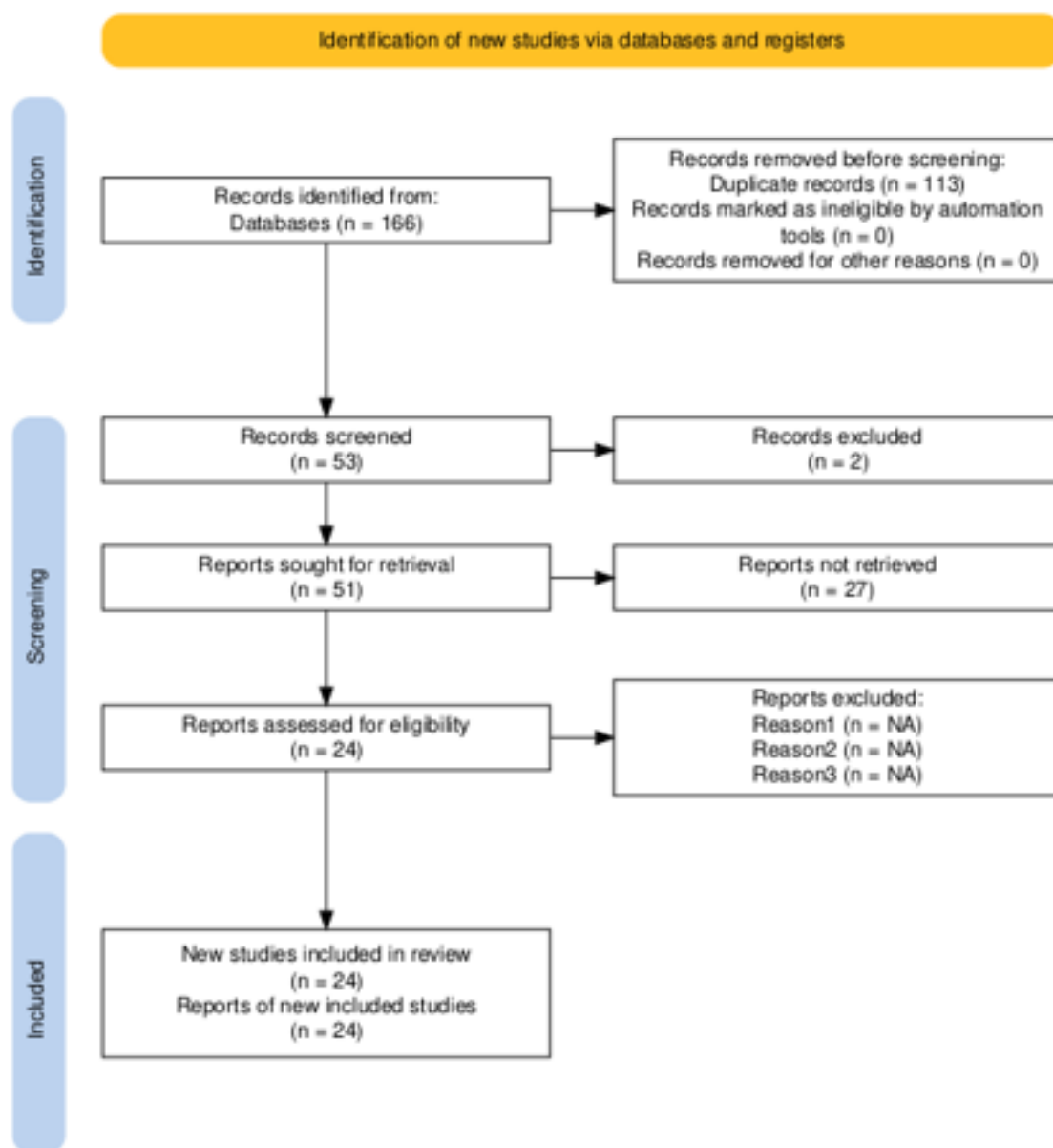


Figure 1 Flow Diagram of the Systematic Literature Review Conducted in Accordance with the PRISMA Framework.

To ensure that the review reflects recent scientific developments in artificial intelligence and supply chain digitalization, a publication-year filter was applied, restricting the dataset to studies published between 2021 and 2026. Consequently, two articles were excluded because they fell outside the specified publication period, leaving 51 articles that satisfied the temporal criterion. In the final eligibility assessment, each remaining article was evaluated against its conformity with the title, scope, and objectives of the present review, leading to the exclusion of 27 articles judged insufficiently relevant to the specific focus on the benefits, risks, and implementation gaps of AI adoption for supply chain visibility in palm oil. Following the completion of all screening and eligibility procedures, a final set of 24 articles satisfied all predefined inclusion criteria and was retained for qualitative synthesis and analysis.

Through this structured PRISMA-based SLR process, the study provides a comprehensive synthesis of current scientific evidence

concerning the role of artificial intelligence in strengthening supply chain visibility within the palm oil industry, emphasizing the technological benefits realized to date, the operational and structural risks encountered during adoption, and the implementation gaps that warrant further attention in future research and industry practice.

Results

The systematic review of the 24 included studies reveals that scholarly attention to artificial intelligence and blockchain-enabled digitalization in the palm oil supply chain has concentrated around five interrelated themes: blockchain-based traceability infrastructure at the smallholder–mill interface, AI-driven forecasting and spatial analytics, certification and regulatory compliance mechanisms, structural barriers to digital transformation, and emerging complementary technologies for governance, finance, and environmental accounting.

Distribution across these themes is uneven. Blockchain-based traceability infrastructure at the smallholder–mill interface accounts for the largest share of the reviewed literature, comprising 7 of the 24 studies (29.2%). This is followed by barriers, readiness, and implementation gaps in digital transformation and emerging complementary technologies for governance, finance, and environmental accounting, each comprising 5 studies (20.8%). Certification, regulatory compliance, and sustainability governance accounts for 4 studies (16.7%), while AI-driven forecasting, spatial analytics, and supply chain optimization represents the smallest cluster, with 3 studies (12.5%).

This concentration around blockchain-based traceability infrastructure is consistent with the structural characteristics of the palm oil supply chain, particularly the difficulty of establishing verifiable origin data across estate, plasma, and independent smallholder channels, making it the most technically tractable entry point for digital intervention. Because traceability from farm to mill is a prerequisite for certification compliance, this theme has likely attracted the largest volume of technical design and prototyping work. The smaller share of studies on AI-driven forecasting and spatial analytics suggests that predictive and optimization-oriented applications remain less prioritized than verification-oriented ones, despite their demonstrated economic and environmental value, pointing to an underexplored opportunity to extend AI beyond documentation toward forward-looking planning. Meanwhile, the near-equal representation of implementation-barrier studies and emerging governance-finance-environmental applications suggests a field that is consolidating its understanding of adoption constraints while only recently beginning to diversify beyond core traceability functions. This distribution, in which verification-oriented applications dominate while predictive and governance-oriented applications remain comparatively underexplored, provides useful context for interpreting the theme-by-theme findings that follow.

Blockchain-based traceability infrastructure at the smallholder–mill interface

The most extensively represented cluster addresses the technical design of blockchain systems that trace fresh fruit bunch (FFB) and crude palm oil (CPO) flows across procurement channels involving plantation-owned estates, plasma farms, and independent smallholders. Foundational architectural work mapped FFB supply from an RSPO-certified estate and an independent smallholder channel onto a Hyperledger Fabric network, enabling low-free-fatty-acid CPO to be traced back to its farm of origin and allowing sustainability information to be shared across the chain.³⁴ Building on this design logic, a conceptual blockchain model for the Indonesian palm oil supply chain was developed using Soft System Methodology and CATWOE analysis, incorporating smart contracts and distributed ledgers across ten categories of actors ranging from smallholders to retailers.³⁵ A parallel transformation-model study applied an As-Is To-Be approach to convert a traditional, vulnerability-prone smallholder information system into a blockchain-based architecture, addressing integrity, transparency, and security concerns directly.³⁶

This design trajectory was subsequently extended toward system hardening, with certificate authorities, a multi-channel data-segregation scheme, and smart contract integration jointly improving throughput, latency, authentication, and resource utility in a smallholder-oriented blockchain prototype.³⁷ At the transactional level, an electronic FFB-offering platform connecting independent farmers, traders, and mills through hash-secured, immutable records has been proposed to address the governance gap affecting

the roughly one-third of Indonesian palm oil output sourced from independent smallholders.³⁸ Complementing these transaction-layer designs, SysML-based smart contract modeling has been used to reduce information asymmetry between supply chain stakeholders by embedding shared, tamper-resistant records directly into contractual execution, thereby lowering reliance on third-party verification.³⁹ Extending traceability further upstream, a bottom-up FFB traceability system combining gap analysis with machine-learning cluster analysis classified 318 independent smallholder plantations into trusted, potential, and low-potential sustainability categories, with 102 of 138 trusted and potential plantations subsequently obtaining RSPO certification.⁴⁰ Collectively, this cluster indicates that blockchain functions primarily as a documentation and coordination layer that strengthens data integrity and inter-actor trust without altering the underlying commercial structure of the supply chain.

AI-driven forecasting, spatial analytics, and supply chain optimization

A second theme concerns the application of machine learning and generative AI to forecasting, spatial mapping, and operational optimization. Generative AI-based demand forecasting using Time-series Generative Adversarial Networks was combined with a province-level Green Supply Chain Sustainability Index incorporating deforestation intensity, land-use efficiency, and RSPO certification status, with results indicating that more than 60 percent of China's projected palm oil imports through 2030 could be met by high-sustainability-index Indonesian provinces without compromising supply security.⁴¹ At the plantation level, an AI-based precision spatial information system was applied in Jambi Province to detect the position, number, and area of smallholder plantations, assess their conformity with regional spatial plans, and estimate farmer income and land-tax potential, thereby strengthening the underlying data foundation required for downstream traceability.⁴²

A further study modeled a two-layer stochastic palm oil supply chain integrating blockchain-enabled certification verification with sustainability investment and carbon cap-and-trade decisions, finding that blockchain adoption reduced the presence of unauthorized products and was associated with a 0.87 percent increase in integrated profit driven by a 1.21 percent rise in demand, while parallel investment in waste-minimization and effluent-treatment technologies lowered solid-waste and wastewater disposal costs by 99.65 percent and 99.26 percent, respectively.⁴³ These findings suggest that AI-enabled analytics contribute measurable economic and environmental value when embedded within broader sustainability and verification frameworks rather than deployed as standalone tools.

Certification, regulatory compliance, and sustainability governance

A third theme examines how digital traceability tools intersect with formal certification schemes and regulatory frameworks such as RSPO, ISPO, and the EU Deforestation Regulation (EUDR). A systematic literature review of 46 peer-reviewed articles found that integrating blockchain, machine learning, and circular economy principles enhances traceability, resource efficiency, and compliance with RSPO and NDPE commitments, while also identifying high implementation costs, limited infrastructure, and smallholder exclusion as persistent constraints on large-scale adoption.⁴⁴ Addressing EUDR compliance specifically, an integrated blockchain traceability model combining smart contracts, role-based access control, and a consumer-facing QR-code interface was validated through stakeholder interviews and a Likert-scale survey, with results indicating improved traceability

integrity, reduced manual verification effort, and closer alignment with RSPO, ISPO, and EUDR requirements simultaneously.⁴⁵

A PRISMA-guided systematic review focused specifically on ISPO certification analyzed 50 studies drawn from 262 identified records, reporting that data integrity was recognized as a key benefit in all 50 studies, vulnerability reduction in 92 percent, efficiency gains in 84 percent, and security enhancement in 76 percent, while implementation challenges were reflected in 90 percent of the reviewed studies, alongside scalability limitations and difficulty reaching smallholder farmers.⁴⁶ Situating these certification-linked findings within a broader sustainability governance context, a review of the Malaysian oil palm industry described how blockchain-enabled traceability supports the sector's long-standing commitment to the people–planet–prosperity pillars of sustainability and helps demonstrate this commitment to customers and international markets.⁴⁷ This cluster of evidence indicates that digital traceability tools are generally positioned in the literature as instruments that reinforce, rather than substitute for, existing certification and regulatory systems.

Barriers, readiness, and implementation gaps in digital transformation

A fourth theme identifies the structural and organizational factors that shape the pace and depth of AI and blockchain adoption. A decision-making readiness framework was developed to help palm oil industry practitioners assess the factors that facilitate blockchain integration into circular economy strategies amid mounting ESG expectations.⁴⁸ At the sector level, a PRISMA-guided systematic review of digital transformation barriers for smart supply chains under an Industry 4.0 paradigm in the Indonesian crude palm oil industry identified 22 distinct barriers grouped into seven categories, situated against a backdrop of comparative disadvantages in efficiency, quality, and transparency relative to other producing countries.⁴⁹ A broader review of digitalization and sustainability in oil palm production similarly highlighted the transformative potential of precision agriculture, data analytics, blockchain, and robotics for resource optimization and supply chain transparency, while identifying high cost, limited technical knowledge, and inadequate infrastructure as the principal barriers to adoption.⁵⁰

Examining a wider set of Industry 4.0 technologies across 98 reviewed studies, plantation mapping, disease detection, and fruit grading emerged as the most common application areas, accounting for 33.1, 24.8, and 10.8 percent of studies respectively, with high implementation cost and workforce skill requirements identified as persistent constraints on wider deployment.⁵¹ Within the Malaysian context specifically, a review of supply chain management challenges under Industry 4.0 adoption noted that heightened sustainability scrutiny has encouraged stakeholders to pursue IoT, AI, digitalization, and automation, while also outlining practical solutions intended to support more effective technological adoption going forward.⁵² Across this cluster, infrastructure limitations, financial cost, workforce capacity, and smallholder reach recur as the most frequently cited implementation gaps, particularly in segments of the supply chain dominated by independent and smallholder producers.

Emerging complementary technologies for governance, finance, and environmental accounting

The final theme captures a smaller but expanding set of studies extending digital innovation beyond core traceability functions. A systematic review of 38 articles examined metaverse-enabled collaborative platforms for palm oil industry stakeholders, finding that

immersive technologies such as virtual and augmented reality, digital twins, blockchain, and AI-driven analytics support transparency and knowledge sharing, while adoption remains constrained by infrastructure gaps, interoperability issues, digital literacy disparities, and regulatory ambiguity.⁵³ In a related vein, a systematic review of Digital Green Management Accounting identified a gap between technological and environmental initiatives on one hand and the managerial accounting mechanisms needed to operationalize them on the other, proposing a conceptual framework that integrates IoT, AI, and blockchain to strengthen real-time monitoring, traceability, and sustainability reporting in support of Sustainable Development Goal 12.⁵⁴

Extending digital traceability into sustainable finance, a conceptual blockchain framework combining Ethereum-compatible smart contracts, ESG oracles, and satellite- and IoT-based compliance verification was proposed to enhance transparency and accountability in green bond financing for sustainable palm oil production, with the stated aim of reducing greenwashing risk and expanding financial inclusion for smallholder farmers.⁵⁵ Environmental accounting applications were also extended to emissions tracking, where a blockchain architecture built on Hyperledger Fabric combined with predictive modeling and deep learning was used to trace greenhouse gas emissions across the cultivation, harvesting, and shipping phases of palm oil production in Sumatra.⁵⁶ Finally, a multiple case study spanning coffee, palm oil, cacao, and rubber value chains found that blockchain-enabled governance varies according to the interaction between system complexity and governance intensity, yielding four distinct governance configurations and reframing blockchain as a context-dependent governance infrastructure rather than a uniform traceability tool.⁵⁷ This cluster suggests that digital innovation in the palm oil sector is gradually broadening from transactional traceability toward integrated governance, financial, and environmental accounting functions.

Taken together, the 24 reviewed studies show a clear concentration of benefits around three measurable outcomes: strengthened data integrity and verification reliability, reduced reliance on manual documentation and third-party intermediaries, and improved alignment with certification and regulatory requirements. At the same time, the literature converges on a consistent set of implementation gaps, most notably high infrastructure and technology costs, limited digital literacy and workforce capacity, interoperability challenges between digital systems and existing institutional processes, and persistent difficulty extending these systems to independent smallholders, who account for a substantial share of global palm oil production. Risk-related considerations are discussed comparatively less often than benefits within the reviewed corpus, and where they are addressed, they center on implementation feasibility and scalability rather than on the underlying legitimacy of digital adoption itself. Geographically, the evidence is concentrated in Indonesia and Malaysia, consistent with the global distribution of palm oil production, which supports the contextual relevance of the findings while indicating comparatively limited cross-regional validation. These patterns collectively provide an empirical foundation for the Discussion section, which interprets the benefits, risks, and implementation gaps identified here in relation to the study's central research questions.

Discussion

The findings synthesized in the preceding section provide a basis for directly addressing the research question guiding this review: *under what conditions does AI adoption enhance supply chain visibility in the palm oil industry, what benefits and risks have been reported, and*

what implementation gaps continue to limit scalable, certification-aligned deployment? Read through the integrated theoretical lens developed in the Literature Review, combining resource-based, information-processing, technology-organization-environment, and institutional perspectives, the reviewed evidence suggests that AI adoption enhances supply chain visibility most reliably when three conditions are jointly present: a defined verification or compliance objective that gives the technology a clear coordination task, a governance layer capable of extending data capture to fragmented upstream actors, and organizational readiness sufficient to sustain the technology beyond a pilot stage.^{34,58} Where these conditions converge, the reviewed literature reports measurable visibility gains; where one or more is absent, particularly organizational readiness or smallholder-level governance capacity, the same underlying technology tends to remain confined to conceptual or prototype status rather than achieving scalable deployment.^{40,50}

The condition of a defined verification objective is most clearly illustrated by the blockchain-based traceability architectures examined in this review. Systems designed explicitly to trace fresh fruit bunch and crude palm oil flows from plantation to mill, whether built on distributed ledger platforms, smart contract frameworks, or hash-secured transaction records, consistently report improvements in data integrity, authentication, and reduced reliance on manual documentation. This pattern is consistent with governance-oriented theorizing of blockchain adoption, which frames the technology less as a predictive tool and more as an infrastructure for enforcing data immutability and verifiable provenance among non-trusting parties.³⁵ In other words, AI and blockchain adoption in palm oil supply chains tends to enhance visibility precisely at the point where verification, rather than optimization, is the primary coordination problem, which aligns with the transaction cost logic proposed in the theoretical synthesis.^{46,59,60}

The second condition, governance capacity extending to fragmented upstream actors, helps explain why visibility gains are unevenly distributed across the supply chain. The most structurally ambitious study in this review, which combined gap analysis with machine-learning cluster analysis to classify several hundred independent-smallholder plantations by sustainability potential, achieved a concrete downstream outcome, with the majority of plantations classified as trusted or potential subsequently obtaining formal sustainability certification.⁴⁰ This result is instructive because it demonstrates that AI-enabled visibility does not merely document existing conditions but can actively enable certification outcomes when paired with a structured pathway from data classification to compliance action. By contrast, studies that model blockchain or AI systems at a conceptual or architectural level, without an explicit mechanism linking smallholder data capture to certification or market access, tend to report technical feasibility without corresponding evidence of adoption at scale.⁶¹ This distinction directly informs the first part of the research question: AI adoption enhances visibility most convincingly when technical design is paired with an institutional pathway, rather than when it is evaluated purely on architectural performance. This evidence reinforces that organizational readiness and governance capacity at the smallholder level are binding conditions for scale: technologically mature solutions cannot deliver inclusive visibility when upstream actors lack reliable data capture, institutional support, or a credible route from digital records to certification and market access.^{28,62,63}

Regarding the benefits reported across the reviewed corpus, three outcomes recur with sufficient consistency to be treated as reasonably well-established findings rather than isolated claims. First, data integrity and verification reliability improve when blockchain and AI

systems replace or supplement manual, paper-based documentation, a pattern confirmed across multiple certification-focused reviews reporting data integrity as a near-universal benefit and vulnerability reduction as a majority outcome among the studies examined. Second, reliance on third-party intermediaries and manual cross-checking is reduced when smart contracts or tamper-resistant records are embedded directly into transactional processes, lowering information asymmetry between supply chain actors. Third, alignment with certification and regulatory frameworks, including RSPO, ISPO, and the EU Deforestation Regulation, improves measurably when traceability tools are designed with these specific compliance requirements in mind rather than as generic digitalization initiatives. These benefits are consistent with the resource-based proposition that visibility functions as a firm-specific capability generating advantage when it is difficult for competitors to replicate quickly, while also reflecting the institutional logic that certification-aligned digital tools are adopted substantially as a response to coercive and normative pressure from regulators and international buyers.^{64,65}

Although most modeling studies in the reviewed corpus do not quantify financing effects directly, the reduction of information asymmetry and improvement in verifiable transparency created by AI-blockchain integration may also affect financial risk. Immutable documentation of FFB origin, when linked with AI-supported monitoring and external sustainability data, can strengthen governance for sustainability-linked financing mechanisms by making environmental and provenance claims more auditable. Recent palm-oil research on blockchain-enabled green-bond financing proposes smart contracts, ESG oracles, and satellite- and IoT-based verification precisely to reduce greenwashing risk and improve financing inclusion. This improved information environment could, in principle, reduce perceived risk premiums and financing frictions for compliant producers; however, the reviewed studies do not yet quantify the magnitude of any cost-of-capital effect, which remains an important empirical question.⁵⁵

The risks and constraints identified in the reviewed literature are, on balance, discussed less extensively than the benefits, and where they appear, they concentrate on implementation feasibility rather than on the legitimacy or desirability of digital adoption itself. The most frequently cited risk-adjacent concern is the exclusion of independent smallholders from systems designed with formal registration or digital literacy assumptions that do not reflect their operating conditions, a constraint noted across certification-focused, barrier-focused, and governance-focused studies alike.⁵⁰ A related but analytically distinct risk concerns interoperability: several studies note that digital traceability systems, once implemented, do not automatically integrate with existing institutional processes, certification audit procedures, or legacy record-keeping practices, which can create parallel rather than unified data infrastructures.⁶⁶ A third risk, discussed comparatively rarely but with clear implications for long-term system integrity, concerns dependency on the completeness and accuracy of the underlying data inputs; because blockchain immutability guarantees that recorded data cannot be altered, it does not by itself guarantee that the data entered was accurate at the point of capture, a distinction largely implicit rather than explicitly theorized in the reviewed studies. Taken together, these risk patterns indicate that AI and blockchain adoption in palm oil supply chains introduces manageable, feasibility-oriented risks rather than fundamental risks to the underlying sustainability objectives the technologies are intended to support.

The implementation gaps identified across the reviewed evidence provide the most direct answer to the third component of the research

question. Four gaps recur with sufficient frequency to be considered structural rather than incidental: infrastructure limitations, particularly reliable connectivity and digital record-keeping capacity in rural production areas; financial cost, both of initial system deployment and of ongoing maintenance; workforce and digital literacy constraints among smallholders and, in some cases, downstream administrative staff; and limited cross-regional validation, with the reviewed evidence concentrated predominantly in Indonesia and Malaysia. These gaps are theoretically consistent with the technology-organization-environment perspective, which conceptualizes technology adoption as contingent on organizational readiness and external institutional pressure rather than on technological capability alone. The reviewed evidence further suggests that the primary constraint on scalable, certification-aligned deployment in the palm oil sector lies in the organizational and financial readiness of smallholders rather than in the technical maturity of AI or blockchain technologies, which appear relatively mature within the reviewed evidence.^{67,68}

Situating these findings within the three theoretical domains proposed in the Literature Review clarifies why visibility gains, benefits, and implementation gaps co-occur in the patterns observed. Resource-based and information-processing theory explain why the documented benefits, particularly data integrity and reduced information asymmetry, translate into measurable value for the actors able to access and use the technology.⁶⁹ Technology-organization-environment and dynamic capability perspectives explain why the same underlying technologies produce uneven outcomes depending on organizational readiness and staged maturity, consistent with the finding that full-system integration linking production, environmental, and market data remains comparatively rare across the reviewed evidence.⁷⁰ Institutional and value chain governance theory, in turn, explain why certification-linked implementations, such as those addressing RSPO, ISPO, and EUDR requirements directly, report more consistent and better-documented outcomes than generically framed digitalization initiatives, since these implementations are responding to a clearly specified external pressure rather than pursuing efficiency gains in the abstract.⁴⁵ This convergence supports the central proposition advanced earlier in this review: visibility, adoption maturity, and institutional pressure function as interacting mechanisms, and implementation gaps become most pronounced precisely where one of these three mechanisms is comparatively weak, most often organizational readiness at the smallholder level.

The implications of these findings extend to both academic and industry audiences. Academically, this review indicates that supply chain visibility frameworks developed primarily in retail and manufacturing contexts require adaptation, rather than direct transfer, when applied to smallholder-dominated agricultural commodities; future theoretical work would benefit from explicitly modeling organizational readiness at the level of the individual smallholder, rather than treating the firm as the unit of analysis, given that a substantial share of palm oil supply chain fragmentation originates at this level. For industry practitioners and certification bodies, the findings suggest that technology investment alone is unlikely to close the implementation gaps identified here; measurable visibility outcomes appear to depend more strongly on pairing digital tools with structured, actor-level pathways to certification, as illustrated by the smallholder classification and certification-linkage findings discussed above, than on the sophistication of the underlying AI or blockchain architecture. For policymakers and regulators, particularly those overseeing compliance with instruments such as the EU Deforestation Regulation, the concentration of implementation gaps around cost and digital literacy indicates that regulatory timelines may need to be considered alongside targeted capacity-building support

for independent smallholders, rather than compliance requirements alone. In terms of future research directions, the comparatively limited geographic scope of the reviewed evidence, concentrated in Indonesia and Malaysia, suggests that cross-country comparative studies involving other palm oil-producing regions would strengthen the generalizability of current findings; similarly, given that most reviewed studies rely on conceptual modeling, architectural design, or single-case validation, future research incorporating longitudinal or multi-site empirical evaluation of deployed systems would help clarify whether the visibility gains reported here persist, scale, and translate into sustained certification outcomes over time. Without accompanying support—including practical training, affordable digital infrastructure, and implementation assistance—compressed compliance deadlines may inadvertently formalize the exclusion of smallholders from regulated export chains, producing socioeconomic costs that undermine the sustainability objectives the regulation is intended to advance.^{28,50}

Conclusion

This review demonstrates that artificial intelligence, when adopted alongside complementary technologies such as blockchain, machine learning, and spatial analytics, enhances supply chain visibility in the palm oil industry most consistently when three conditions are jointly present: a clearly defined verification or compliance objective, a governance mechanism capable of extending data capture to fragmented upstream actors, and sufficient organizational readiness to sustain the technology beyond an initial pilot phase. Where these conditions converge, the reviewed evidence points to measurable improvements in data integrity, verification efficiency, and reduced reliance on manual documentation and third-party intermediaries. Where one or more of these conditions is absent, particularly organizational readiness among independent smallholders, the same technologies tend to remain at a conceptual or architectural stage rather than achieving scalable, operational deployment.

The benefits reported across the reviewed literature center on three recurring outcomes: strengthened data integrity and verification reliability, reduced information asymmetry between supply chain actors through smart contracts and tamper-resistant records, and improved alignment with certification and regulatory frameworks such as RSPO, ISPO, and the EU Deforestation Regulation. Risks and constraints, while discussed comparatively less than benefits, concentrate on implementation feasibility rather than on the underlying legitimacy of digital adoption itself, most notably the exclusion of independent smallholders from systems designed around formal registration or digital literacy assumptions, limited interoperability between new digital systems and existing institutional processes, and residual dependency on the accuracy of data entered at the point of capture, which blockchain immutability does not by itself resolve.

The implementation gaps identified across the reviewed evidence are structural rather than incidental, recurring most consistently around four dimensions: infrastructure limitations in rural production areas, the financial cost of deployment and maintenance, workforce and digital literacy constraints among smallholders, and limited cross-regional validation, with the available evidence concentrated predominantly in Indonesia and Malaysia. Taken together, these findings indicate that the primary constraint on scalable, certification-aligned deployment of AI-enabled visibility solutions in the palm oil sector lies less in the technical maturity of the tools themselves, which appear comparatively well developed, and more in the organizational, financial, and institutional readiness of the actors expected to adopt and sustain them, particularly at the smallholder level.

These conclusions carry practical relevance for palm oil producers, certification bodies, and policymakers seeking to advance verifiable, technology-supported traceability, and they underscore the value of pairing technological investment with structured, actor-level pathways to certification rather than treating digital adoption as a standalone solution. As artificial intelligence and blockchain technologies continue to mature within agricultural commodity systems, sustained attention to organizational readiness and smallholder inclusion is likely to determine whether the visibility gains documented in this review translate into broader, long-term improvements in the transparency and accountability of palm oil supply chains.

Acknowledgements

None.

Conflicts of interest

The author declares there is no conflict of interest.

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