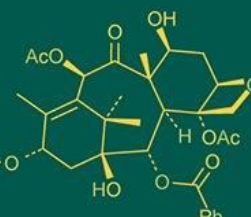
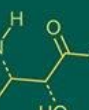
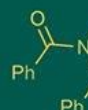


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Enhancing transparency and trust in agri-food supply chains through blockchain technology: A review

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Abstract

The agri-food sector continues to face serious challenges related to lack of transparency, increasing incidents of fraud, fragmented supply chains, and declining consumer trust. These issues not only threaten food safety and quality but also weaken the sustainability and resilience of agricultural systems. In recent years, blockchain technology has gained considerable attention as a transformative digital infrastructure capable of addressing these concerns through its decentralized, immutable, and transparent ledger mechanism. This review paper critically examines existing literature on blockchain applications in agriculture, with particular emphasis on its role in strengthening transparency, enhancing traceability, and mitigating fraudulent practices across agri-food supply chains. The study synthesizes current research on blockchain-enabled solutions such as traceability platforms, smart contracts, secure data-sharing systems, and decentralized agricultural finance. It further explores the integration of blockchain with emerging technologies, including the Internet of Things (IoT) and Artificial Intelligence (AI), to support real-time monitoring, predictive analytics, and informed decision-making in smart farming environments. Despite the growing body of research and pilot initiatives, blockchain adoption in agriculture remains limited due to high implementation costs, technological complexity, infrastructure gaps, and low digital awareness among smallholder farmers. This review identifies major opportunities, constraints, and future research directions associated with blockchain deployment in the agri-food sector. The findings suggest that blockchain technology holds significant potential to enhance trust, accountability, and operational efficiency, thereby contributing to the development of more transparent, resilient, and sustainable agricultural supply chains.

Keywords: Blockchain technology, agri-food supply chains, transparency, traceability, fraud mitigation, digital transformation

Introduction

The agri-food sector plays a central role in ensuring global food security, rural livelihoods, and economic development. However, contemporary agri-food systems are increasingly challenged by fragmented supply chains, limited transparency, and growing incidents of fraud. Practices such as the circulation of counterfeit agricultural inputs, food adulteration, and misrepresentation of product origin continue to undermine food safety, weaken market efficiency, and erode consumer confidence. In addition, inadequate traceability mechanisms restrict the ability of stakeholders to monitor the movement of food products across production, processing, and distribution stages, thereby complicating quality assurance and regulatory enforcement.

In response to these challenges, blockchain technology has emerged as a promising digital infrastructure for strengthening governance and accountability in agri-food supply chains. Blockchain operates as a decentralized and distributed ledger in which transactions are chronologically recorded, cryptographically secured, and collectively validated by network participants. This architecture creates a tamper-resistant environment where data, once entered, cannot be altered without network consensus. By reducing dependence on centralized intermediaries, blockchain enhances data integrity, limits single-point failures, and supports greater institutional trust among supply chain actors.

A key contribution of blockchain technology lies in its capacity to enhance transparency and traceability across complex agricultural networks. Through blockchain-enabled platforms, information related to farm practices, processing conditions, logistics activities, and certification records can be securely documented and shared among authorized participants.

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Such systems allow products to be digitally traced from origin to point of sale, enabling stakeholders to verify quality attributes, production standards, and compliance with regulatory or sustainability requirements. Improved transparency not only strengthens consumer confidence but also supports ethical sourcing, environmental accountability, and performance monitoring across agri-food systems.

Blockchain further offers important mechanisms for mitigating fraud in agricultural markets. Immutable digital records facilitate the authentication of agricultural inputs, reducing the circulation of counterfeit seeds, fertilizers, and pesticides. Similarly, blockchain-based traceability infrastructures limit opportunities for food fraud by enabling verification of labeling claims, geographic origin, and transaction histories. The incorporation of smart contracts self-executing digital protocols embedded within blockchain networks extends these benefits by automating contractual obligations such as payment execution, quality verification, and insurance settlements. Automation of these processes reduces disputes, shortens transaction cycles, and enhances trust among producers, processors, and distributors.

Beyond traceability and fraud prevention, blockchain also supports improved agricultural data governance. Secure, decentralized data systems enable the reliable sharing of information related to crop performance, climatic conditions, soil quality, and farm management practices. Such environments facilitate collaborative decision-making, strengthen research and extension services, and promote evidence-based agricultural planning. By integrating transparent record-keeping with digital innovation, blockchain creates opportunities for more inclusive and data-driven agricultural ecosystems.

Collectively, these capabilities position blockchain technology as a strategic tool for promoting sustainability and resilience in the agri-food sector. Transparent supply chains support responsible resource management, enhance market access for smallholder producers, and contribute to fairer value distribution. As digital agriculture continues to evolve, blockchain-enabled systems are expected to play an increasingly important role in building trustworthy, efficient, and sustainable food systems. This review therefore examines current research on blockchain applications in agriculture, with particular emphasis on transparency enhancement, fraud mitigation, and the emerging technological pathways shaping agri-food supply chains.

2. Need of the Study

The agriculture and agri-food sectors form the backbone of global food systems, yet they continue to face persistent challenges related to supply chain inefficiencies, limited transparency, and the rising incidence of fraud. The circulation of counterfeit agricultural inputs, mislabeling of food products, and lack of reliable traceability mechanisms not only compromise food safety but also weaken farmer incomes and consumer confidence. Despite increasing regulatory attention and technological advancement, existing information systems often remain fragmented, centralized, and vulnerable to manipulation, making effective monitoring and accountability difficult to achieve.

In recent years, blockchain technology has been widely proposed as a disruptive solution capable of transforming agri-food supply chains through decentralized data management, immutable record-keeping, and automated

transaction protocols. While conceptual discussions and pilot initiatives are rapidly expanding, the practical implications of blockchain adoption in agriculture are still insufficiently synthesized within academic literature. Existing studies are scattered across disciplines such as information technology, supply chain management, and agricultural economics, limiting the development of a coherent understanding of how blockchain can specifically address transparency and fraud-related challenges in agriculture.

Furthermore, real-world implementation of blockchain in the agri-food sector remains constrained by high costs, infrastructural limitations, regulatory uncertainty, and low digital literacy among smallholder farmers. There is a clear need for an integrated review that consolidates current knowledge, identifies dominant application areas, evaluates adoption barriers, and highlights research gaps. This study therefore seeks to systematically examine the emerging body of literature on blockchain in agriculture, with the objective of providing structured insights for researchers, policymakers, and industry stakeholders aiming to design transparent, trustworthy, and sustainable agri-food systems.

This review has been undertaken with the following objectives:

1. To examine how blockchain technology can address key issues of transparency and fraud in the agri-food sector.
2. To identify the major factors influencing the adoption of blockchain in agricultural supply chains.
3. To explore the practical implications of blockchain applications for key stakeholders, including farmers, policymakers, and consumers.
4. To discuss potential strategies for overcoming barriers to the widespread adoption of blockchain technology in agriculture.

As global food systems become more complex and interconnected, the need for secure, reliable, and transparent supply chains is more urgent than ever. This study aims to provide a comprehensive review of how blockchain technology can transform agriculture by improving trust, efficiency, and sustainability. The findings will be particularly valuable for policymakers, industry leaders, and researchers seeking innovative solutions to address fraud and enhance transparency in the agri-food sector.

3. Materials and Methods

This review paper adopts a structured and systematic approach to examine existing literature on the applications of blockchain technology in agriculture, with particular emphasis on transparency enhancement and fraud reduction in agri-food supply chains. A comprehensive literature search was conducted across major academic databases, including Scopus, Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar. Relevant studies were identified using combinations of keywords such as *"blockchain in agriculture," "agri-food blockchain," "supply chain transparency," "traceability systems,"* and *"fraud prevention using blockchain."* The selection of literature was guided by clearly defined inclusion and exclusion criteria. Peer-reviewed journal articles, conference proceedings, and authoritative institutional reports focusing on blockchain-based solutions in agriculture, food supply chains, traceability mechanisms, smart contracts, and fraud

mitigation were included. Studies unrelated to agricultural applications, purely technical blockchain papers without sectoral relevance, and non-scholarly sources were excluded. After initial screening of titles and abstracts, full-text articles were reviewed to ensure relevance and quality. The selected literature was then systematically analyzed using a qualitative thematic analysis approach. Key findings were organized into major thematic categories, including blockchain-enabled traceability, transparency frameworks,

fraud prevention mechanisms, integration with emerging technologies, and implementation challenges. This approach enabled the synthesis of dispersed research evidence into a coherent analytical framework, highlighting dominant research trends, practical applications, and gaps that require further investigation.

4. Applications of Blockchain Technology in Agriculture

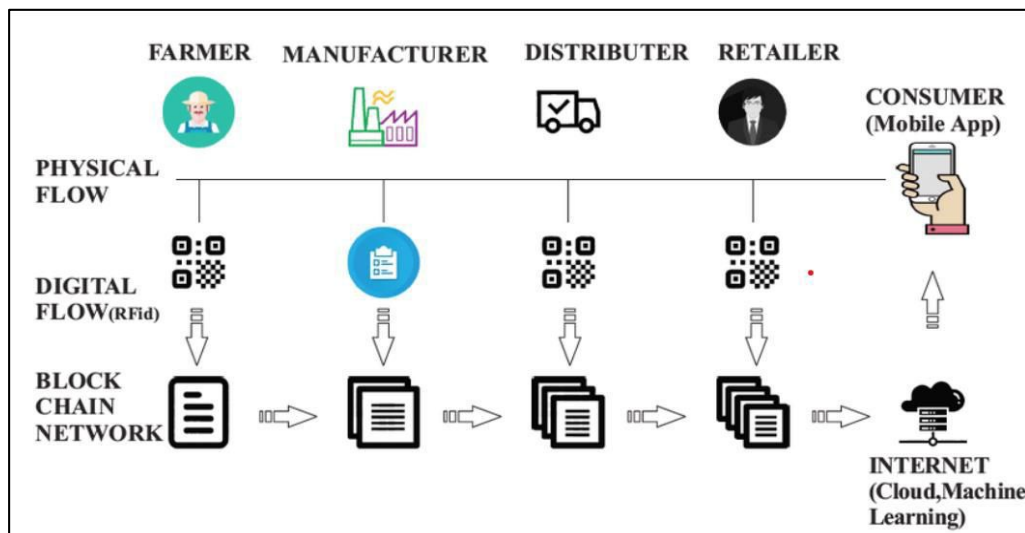


Fig 1: Blockchain-enabled agri-food supply chain framework illustrating physical and digital flows, blockchain network integration, and its role in enhancing transparency, traceability, and fraud reduction (adapted from Subramanian *et al.*, 2019) ^[30].

Figure 1 illustrates the conceptual framework of a blockchain-enabled agri-food supply chain supporting transparency and traceability (adapted from Subramanian *et al.*, 2019) ^[30]. Blockchain technology is increasingly recognized as a foundational digital infrastructure capable of supporting the modernization of agricultural systems. The reviewed literature indicates that one of the most prominent application areas of blockchain lies in agri-food supply chain management, where it enables the secure recording and sharing of transactions across production, processing, storage, transportation, and retail stages. By establishing a shared and tamper-resistant ledger, blockchain reduces information asymmetry among stakeholders and enhances coordination between farmers, processors, logistics providers, and market intermediaries.

Beyond supply chain coordination, blockchain is also applied in agricultural data governance. Blockchain-based platforms facilitate secure storage and controlled sharing of data related to crop production, farm operations, environmental conditions, and certification records. These systems support collaboration among farmers, researchers, and agribusiness firms while preserving data integrity and ownership rights. Another rapidly growing application domain involves the use of smart contracts, which automate contractual processes such as procurement agreements, insurance claims, subsidy disbursement, and payment settlements. Automation through smart contracts reduces transaction delays, lowers administrative costs, and limits disputes arising from manual verification processes.

Blockchain applications are further expanding into agricultural finance and risk management. Limited access to formal credit, lack of transaction transparency, and delayed payments remain major barriers for farmers, particularly smallholders. Blockchain-enabled financial systems create

verifiable transaction histories and digital farm records that can strengthen trust between farmers and financial institutions. As a result, blockchain can support decentralized financing models, transparent insurance mechanisms, and faster payment systems, thereby contributing to more inclusive and efficient agricultural value chains.

5. Blockchain for Transparency and Traceability in Agri-Food Supply Chains

Transparency and traceability constitute central themes across blockchain-based agricultural research. Traditional agri-food supply chains are often characterized by fragmented information systems, making it difficult to trace products across multiple intermediaries. Blockchain addresses this limitation by enabling the continuous documentation of verified information throughout the supply chain lifecycle. Production practices, processing conditions, logistics parameters, and certification data can be recorded in chronological order and accessed by authorized stakeholders.

Such traceability frameworks allow agricultural products to be digitally tracked from farm to consumer, enhancing visibility and accountability at each stage. Improved transparency supports quality assurance, regulatory compliance, and sustainability monitoring. Consumers benefit from access to reliable product information related to origin, authenticity, and production standards, while firms gain improved capacity to detect inefficiencies, monitor compliance, and respond rapidly to safety incidents. Consequently, blockchain-enabled transparency systems are widely viewed as a critical instrument for strengthening trust and governance in modern agri-food networks.

6. Role of Blockchain in Reducing Fraud in Agriculture

The reviewed literature consistently identifies fraud as a major vulnerability within agri-food systems, affecting both agricultural inputs and food products. Counterfeit seeds, fertilizers, and pesticides compromise farm productivity, while food adulteration and mislabeling threaten consumer safety and market credibility. Blockchain's immutable ledger structure provides a reliable mechanism for documenting product origins, transaction histories, and certification records, making unauthorized alterations extremely difficult.

By enabling product authentication and verifiable documentation, blockchain limits opportunities for fraudulent substitutions, false labeling, and unauthorized replication. In addition, smart contracts strengthen fraud mitigation by embedding compliance rules directly into digital transactions. Payments, insurance disbursements, and procurement contracts can be automatically executed only when predefined quality and delivery conditions are fulfilled. This programmable enforcement reduces reliance on manual oversight, lowers transaction risk, and enhances accountability among supply chain actors. Collectively, these mechanisms position blockchain as a powerful digital tool for strengthening integrity and trust within agricultural markets.

7. Integration of Blockchain with IoT and Artificial Intelligence

Recent studies increasingly highlight the convergence of blockchain with emerging digital technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI). IoT devices enable real-time data collection related to soil conditions, crop health, weather variability, storage environments, and logistics operations. When integrated with blockchain, such data can be securely recorded and validated, creating trustworthy digital records that enhance transparency and monitoring capacity.

Artificial intelligence further extends this technological ecosystem by enabling predictive analytics, anomaly detection, and decision-support systems. AI-driven models applied to blockchain-secured datasets can assist in yield forecasting, disease detection, climate risk assessment, and resource optimization. This convergence transforms blockchain from a passive data repository into an active agricultural intelligence infrastructure capable of supporting precision farming, adaptive risk management, and evidence-based policy design.

8. Benefits of Blockchain Technology in the Agri-Food Sector

Blockchain technology offers multiple structural and operational benefits across agri-food systems. One of its primary contributions lies in strengthening trust among stakeholders by creating a shared, verifiable source of information regarding farm operations, product movement, and transactional histories. This transparency reduces information asymmetry and fosters cooperative relationships among farmers, processors, distributors, retailers, and consumers.

Blockchain further facilitates efficient information exchange across the supply chain by enabling real-time access to tamper-resistant data. Such visibility improves coordination, supports quality monitoring, and enhances responsiveness to safety incidents or market fluctuations. By automating

documentation, verification, and payment processes through smart contracts, blockchain significantly reduces transaction costs and administrative burdens. This streamlining of processes contributes to faster settlements, improved cash flows, and more efficient market participation, particularly for smallholder farmers.

In addition, blockchain enhances food safety and authenticity by enabling continuous traceability and reliable product authentication. The ability to verify origin, handling conditions, and certification records strengthens compliance mechanisms, reduces the circulation of counterfeit goods, and increases consumer confidence. Collectively, these benefits position blockchain as a digital enabler capable of improving efficiency, equity, and resilience within agri-food value chains.

8. Limitations and Challenges of Blockchain Adoption

Despite its promising potential, the literature consistently highlights significant constraints affecting blockchain adoption in agriculture. High implementation and maintenance costs remain a major barrier, particularly in developing-country contexts where digital infrastructure and investment capacity are limited. The technological complexity of blockchain systems, coupled with interoperability challenges among platforms, further complicates large-scale deployment.

Limited digital literacy, lack of technical expertise, and low awareness among smallholder farmers also restrict effective participation in blockchain-enabled systems. In addition, governance-related concerns such as data ownership, privacy protection, regulatory uncertainty, and standardization frameworks remain insufficiently addressed. The reliability of blockchain records ultimately depends on the quality of data inputs, raising concerns related to data accuracy, verification mechanisms, and incentive structures for truthful reporting.

These limitations indicate that blockchain adoption in agriculture requires not only technological readiness but also institutional support, policy alignment, and inclusive capacity-building initiatives to ensure sustainable and equitable implementation.

10. Discussion

The synthesis of reviewed studies suggests that blockchain technology represents more than a technological upgrade; it constitutes a potential structural transformation of agri-food systems. By enabling decentralized trust, immutable record-keeping, and automated transaction governance, blockchain reshapes how transparency, accountability, and coordination are operationalized across agricultural value chains.

The strongest consensus within the literature concerns blockchain's role in enhancing transparency and traceability, which directly contributes to improved food safety, fraud mitigation, and regulatory compliance. Integration with IoT and AI further expands blockchain's functional scope by supporting real-time monitoring, predictive analytics, and adaptive decision-making frameworks. However, the gap between conceptual promise and large-scale practical implementation remains substantial. Economic constraints, infrastructural limitations, regulatory ambiguity, and human-capacity challenges continue to restrict widespread adoption.

Therefore, the successful institutionalization of blockchain in agriculture will depend on the development of scalable

architectures, farmer-centric platforms, supportive policy environments, and cross-sector collaboration among governments, industry actors, and research institutions. Without such integrative strategies, blockchain risks remaining confined to isolated pilot initiatives rather than becoming a systemic driver of agricultural transformation.

11. Conclusion

Blockchain technology holds considerable potential to address long-standing challenges in the agricultural sector, particularly those related to transparency deficits, fraudulent practices, and supply chain inefficiencies. Its decentralized and immutable architecture enables the secure documentation of transactions across production, processing, and distribution stages, thereby strengthening traceability, accountability, and trust among agri-food stakeholders.

The review highlights blockchain's capacity to mitigate food fraud, authenticate agricultural inputs, and support automated governance mechanisms through smart contracts. Furthermore, integration with emerging technologies such as IoT and artificial intelligence enhances blockchain's role in enabling real-time monitoring, predictive analytics, and data-driven agricultural management. These capabilities collectively contribute to the development of more efficient, resilient, and sustainable agri-food systems.

Nevertheless, the realization of these benefits remains contingent upon overcoming critical barriers, including high implementation costs, technological complexity, infrastructural gaps, and limited digital capacity among farming communities. Policy support, institutional coordination, and inclusive innovation frameworks will be essential to ensure that blockchain solutions are scalable, affordable, and aligned with the needs of diverse agricultural stakeholders. Future research should prioritize empirical validation, governance models, and integration strategies capable of translating blockchain's conceptual promise into measurable development outcomes. By addressing these challenges, blockchain technology can serve as a transformative instrument in building transparent, trustworthy, and sustainable global food systems.

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