



REVIEW ARTICLE

Cyber-secured agriculture (part 2): Blockchain nexus

T Porchelvan^{1*}, P Sudhakar^{1*}, S Ramesh¹, M Meyyappan¹, P Balabaskar² & K Akshaya Dharshini¹

¹Department of Agronomy, Faculty of Agriculture, Annamalai University, Annamalai Nagar 608 002, Tamil Nadu, India

²Department of Plant Pathology, Faculty of Agriculture, Annamalai University, Annamalai Nagar 608 002, Tamil Nadu, India

*Correspondence email - porchelvanporz@gmail.com; sudha.au.in@gmail.com

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Abstract

Data is not just information; it's the bloodstream of the hyper-connected digital ecosystem. Anchored in this premise, part 1 of this review series, entitled "big data genesis," unveiled the digital behemoth by tracing the historical evolution of data from rudimentary records to the era of planetary-scale digital generation. It revealed how the data has transitioned from passive documentation into a powerful active force that governing the entire economic system, technologies and the decision-making across the various domains through the big data analytics. Within agriculture domain, big data has become an important factor of the intelligent farming systems, enabling the real-time decision-making and the predictive precision. However, as agriculture transited from the digital intelligence to digital dependence, a significant vulnerability arises without the trust, the data will lack its value. The very same datasets that support the precision farming and the advanced analytics will become liabilities, if they are falsified, fragmented or manipulated without adequate authentication. Therefore, beyond simply generating and analysing the agricultural big data, there is an imperative need for an advanced technological framework capable of ensuring the transparency, integrity and verifiability of the digital agricultural records. As an essential sequential continuum in this digital agricultural odyssey from the data intelligence to the data trust architecture: part 2, entitled "Blockchain nexus", explores the decentralised core that underpins the contemporary cryptocurrencies and the digital economies. Building upon this evolution, the central hypothesis of this present paper proposes that, integrating the blockchain technology with the agriculture can pioneer a secure, transparent, tamper-proof and the traceable data ecosystem for the modern farming systems. This architecture enables the complete end to end traceability of the agricultural inputs, farming practices and the outputs, thereby enhancing the credibility of organic agriculture and sustainable farming claims, while preserving the data integrity across the entire agricultural-value chain. By enabling this verifiable provenance and the secure digital records, this framework aims to reinforce the trust of consumer, improve the regulatory compliance and promote the emergence of cyber-secured agriculture system.

Keywords: big data; blockchain; cyber-secured agriculture; traceability; transparency

Introduction

In the era of algorithms, the technological innovation is reinventing the modern agriculture, where internet of things (IoT), artificial intelligence (AI) and big data analytics are redefining the concept of farm intelligence and propelling productivity to unprecedented levels (1-5). Despite the expeditious technological ascendancy, a fundamental challenge remains unaddressed, that is authenticity. The agricultural domain remains grapple with the falsified organic farm data, unverifiable certifications and the opaque supply chains, that undermine consumer trust and erode the farmer's credibility. While IoT installed systems can detect the temperature, humidity and the storage conditions, they remain incapability to ensure the end-to-end traceability of agricultural data. Similarly, AI can predict the yields, risks and prices using the previous historical datasets, but it cannot ensure that, whether the input agricultural data is real or manipulated. Therefore, despite their significant transformative power, the existing digital technologies, remain constrained by the lack of embedded trust mechanisms. These restraints require the necessity for an even more sturdy technological paradigm, that capable of embedding traceability, transparency and the verifiable authenticity at the core of the modern agriculture.

Blockchain technology, originally designed to underpin cryptocurrency ecosystems, has now transcended the financial domain to materialised as a powerful force in digital agriculture. By pioneering a decentralised and tamper-proof ledger, it enables a rigorous traceability, real-time monitoring process and automated regulatory compliance through the smart contracts. This cryptographic foundation offers a very powerful mechanism to alleviate persistent difficulties in the agricultural systems, including the data falsification, unverifiable certifications, fragmented supply chains and the weak accountability across stakeholders (6-8). By delivering perpetual transparency across the entire agricultural-food value chain from farm production to final consumption, this blockchain-based systems holds a substantial potential to minimise the spoilage, fraud and functional inefficiencies, thus mitigating the food adulteration and advancing the sustainability objectives. Despite of these advantages, the large-scale adoption of blockchain in agriculture domain remains constrained by challenges related to scalability, system interoperability, digital literacy and regulatory ambiguity (9, 10). However, despite the growing body of literature, there remains a critical gap in systematically linking blockchain's core technological features with specific agricultural challenges such

as certification fraud, data manipulation and trust deficits in agri-food systems. Therefore, this review aims to critically analyse the role of blockchain technology in addressing key issues of transparency, traceability and data security in agriculture, with a specific focus on its practical applicability and integration with existing digital technologies. Within this background, the present review critically evaluates the contemporary developments in blockchain-enabled transparency, traceability and the cybersecurity for agricultural systems. Through a comprehensive synthesis of evidence from both scholarly literature and practical implementations, this study seeks to elucidate existing technological capabilities, assess their prospective contribution to agricultural traceability and delineate future research directions for secure and sustainable agri-food ecosystems.

Materials and Methods

Review design

This study employs a structured narrative review methodology, which is suitable for rapidly advancing and interdisciplinary fields such as blockchain-driven secured architectures in the digital agriculture. Although this review is narrative in the form, it incorporates a defined procedural component, including transparent source selection, eligibility criteria and the thematic synthesis, were incorporated to strengthen the methodological rigour and ensure the reproducibility.

Source identification and search strategy

A comprehensive literature search was carried out across the prominent scientific and technical databases, such as Google

Scholar, Scopus, Web of Science, SpringerLink, ScienceDirect and IEEE Xplore. This review covered the period spanned from January 2010 to January 2025 to encompass the emergence of digital agriculture and the integration of blockchain technologies within agricultural-food systems. Search strategies were designed using combinations of the keywords such as digital farming, blockchain technology, cyber-secured agriculture, distributed ledger, agricultural traceability, supply-chain transparency, smart contracts and the decentralised systems.

Screening and selection process

The study selection followed a four-stage filtering framework. Initially, 162 records were identified across all databases. After removing 31 duplicates, 131 unique records remained. During title and abstract screening, 72 records were excluded based on relevance to blockchain applications in agriculture and allied sectors, leaving 59 studies for further evaluation. Subsequently, full-text assessment led to the exclusion of 21 articles due to insufficient technical depth or lack of direct relevance. Finally, 38 studies were included in the qualitative synthesis and the complete study selection process is illustrated in Fig. 1.

Inclusion and exclusion criteria

Inclusion criteria

Studies were considered eligible if they:

- (i) investigated blockchain or about distributed ledger technologies
- (ii) focused on the agricultural or agricultural-food systems
- (iii) were published in English in the scholarly journals, conference proceedings

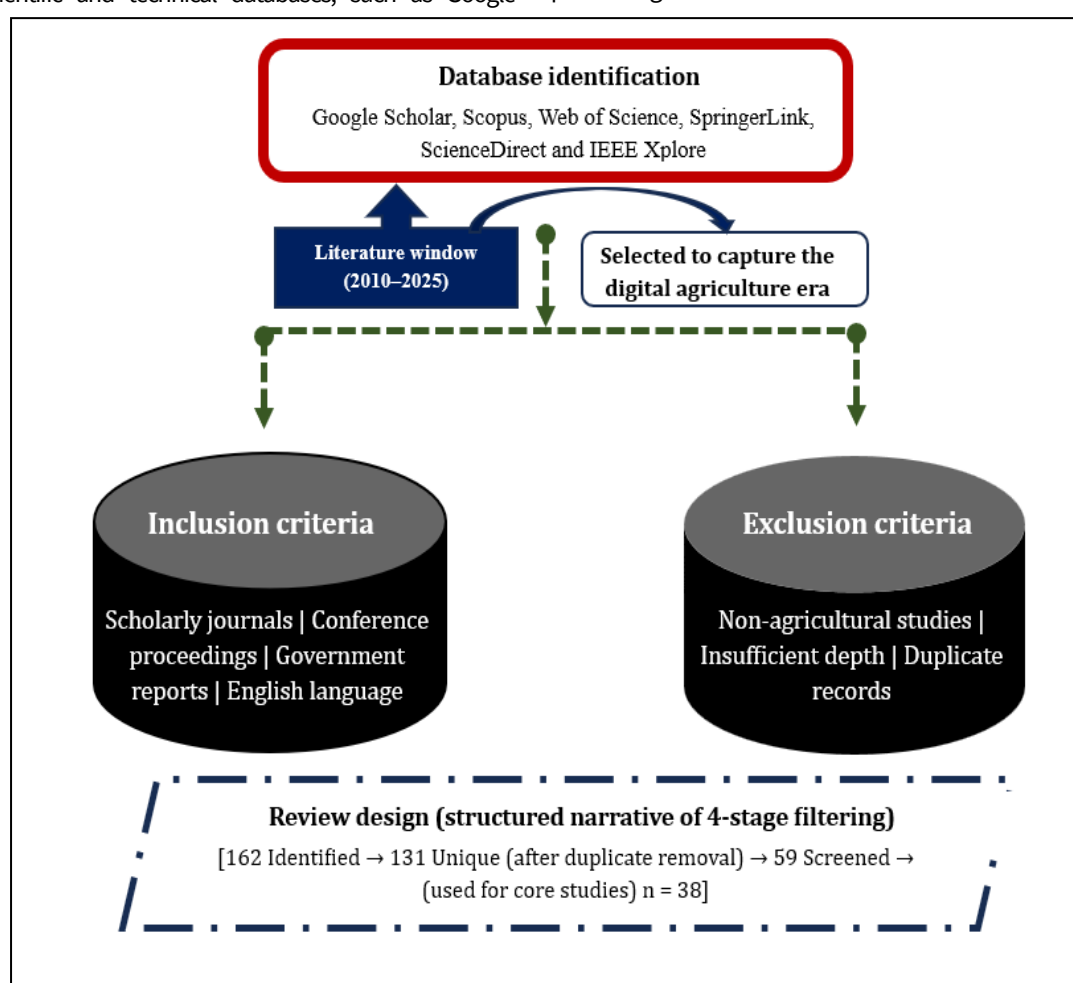


Fig. 1. Multi-stage literature selection and analytical framework illustrating the methodology of the structured narrative review.

Exclusion criteria

Studies were considered non-eligible for inclusion if they:

- (i) focused exclusively on non-agricultural sectors
- (ii) did not provide sufficient analytical or technical depth
- (iii) appeared as duplicated across multiple databases; or had full texts that are unavailable

Data compilation

The relevant information was extracted from each selected study, including the publication year, geographical context, nature of the research (conceptual, applied or experimental), the type of blockchain architecture utilised, the stage of the agricultural system examined (production, logistics, certification or retail) and the reported outcomes and the limitations.

Thematic analysis

The reviewed literature was organised using an inductive thematic approach. Recurrent concepts and technological patterns were manually identified and consolidated into principal thematic categories, without the assistance of automated qualitative analysis tools. These themes were subsequently refined through an iterative process to reflect prevailing research trajectories and emerging paradigms in the blockchain-driven agricultural security.

Transparency and replicability

While the present review does not fully conform to formal preferred reporting items for systematic reviews and meta-analyses (PRISMA) systematic review framework, the essential methodological components such as database selection, keyword formulation, screening procedures and the eligibility conditions are explicitly described to promote transparency and facilitate reproducibility in future investigations.

Results and Discussion

Blockchain technology

Blockchain was first conceptualised in the year 2008 by Satoshi

Nakamoto, through the publication of the white paper bitcoin: a peer-to-peer electronic cash system, which introduced a first decentralised mechanism for verifying and recording the digital transactions. Blockchain technology is a decentralised, distributed ledger system which records the transactions in a continuous series of a linked data blocks, in which each are cryptographically secured and chronologically ordered (11, 12). Unlike the traditional centralised databases, blockchain networks work on a peer-to-peer basis, in which each participant or node, maintains a synchronised copy of the entire ledger. Every transaction was validated through a consensus mechanism namely, proof of work or proof of stake, before being permanently appended to the chain, ensuring data immutability and resistance to tampering (13).

The fundamental core feature of blockchain is its traceability, transparency and the auditability: all the authorised participants can trace the entire history of any transaction, which is particularly valuable for the supply chain management and the regulatory compliance in agriculture domain (14). Moreover, the blockchain platforms frequently support the deployment of smart contracts, which are self-executing programs that automates agreements and the business logic, further minimising the risk of fraud and human error (15, 16). These properties enable the blockchain, a compelling solution for enhancing the data security, provenance and trust in increasingly digital and interconnected agricultural-food systems (10).

Core pillars of blockchain

The core foundational pillars of the blockchain technology includes cryptography, decentralisation, immutability, transparency, peer verification, robust consensus mechanisms and pseudonymity. To visualise these core principles of blockchain, a schematic representation of the structural and functional pillars that collectively sustain the blockchain ecosystem, illustrating how cryptographic trust is established in a decentralised digital environment has been represented in Fig. 2.

Decentralisation ensures that no single central authority governs or control the ledger; instead, agreement is established

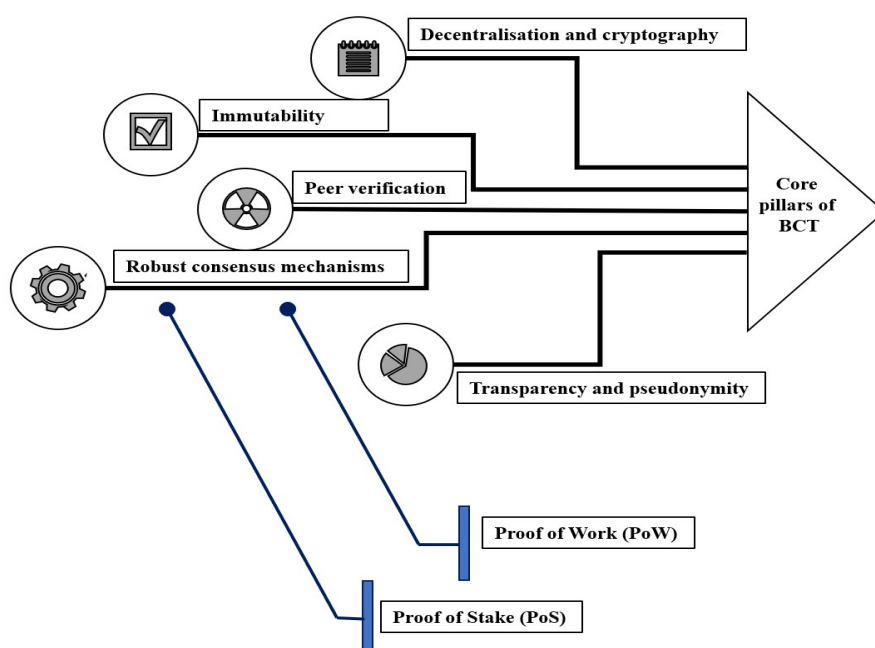


Fig. 2. Pillars of trust: The structural architecture of blockchain technology.

across a distributed network of nodes, thereby improving the system resilience and reduce the risk of single points of failure (17). Immutability denotes the near-impossibility of retroactively modifying records once they have been recorded on the blockchain, since any modification would require prohibitive computational effort. This characteristic of blockchain guarantees a high level of historical permanence and data integrity (18). Transparency provides all authorised participants to verify and view the ledger entries, fostering accountability, auditability and the trust among stakeholders (19). The consensus mechanisms, involves proof of work (PoW) and proof of stake (PoS), coordinate transaction validation and maintain the uniformity of the ledger across the network, therefore preventing the fraudulent activities such as double spending and the unauthorised record manipulation (20). Pseudonymity denotes the representation of each participant through cryptographic addresses rather than the explicit personal identities. In blockchain systems, the users interact through the public or private key pairs, enabling transactions to be conducted without directly revealing real-world identities. This property also provides a degree of privacy while preserving the traceability of transactional behaviour across the ledger. Unlike the full anonymity, pseudonymity allows each of the activities to be audited and linked over time, thereby balancing the individual privacy with system-level transparency and accountability. Finally, the cryptographic security employs advanced techniques involving hashing algorithms and digital signatures to encrypt data, authenticate participants and thereby safeguard the system against the malicious interference and unauthorised access (19).

Technical architecture

To understand how the core foundational pillars of the blockchain technology are being operationalised in practice, it is essential to examine its internal technical foundations. At the most fundamental level, the blockchain functions through a sequential and cryptographically secured data flow. First, the transactional data (e.g., input records, sensor outputs or transactional events) enter the network and are grouped into a candidate block. Each block

contains a structured set of transactions, a timestamp and a reference to the cryptographic hash of the previous block. Next, a nonce (number used once) is introduced and modified during the validation process. This nonce is combined with the transaction data and the previous block's hash to generate and provide a new cryptographic hash, a fixed-length alphanumeric string, which uniquely represents the block's contents. In PoW systems, the nonce is repeatedly adjusted until the resulting hash satisfies the predefined network conditions (e.g., leading zeroes), therefore demonstrating computational effort and ensuring the resistance to malicious manipulation. Once a valid hash is created, the block is formally sealed and then appended to the existing ledger. Through this entire process, individual blocks were cryptographically linked and forming a continuously growing chain of records. This chaining mechanism ensures the immutability, as any of alteration in a previously stored or linked block would require recalculating the hashes of all subsequent blocks, an operation that is computationally prohibitive under decentralised consensus. Consequently, the blockchain evolves as a distributed, tamper-resistant and verifiable chronological archive of transactions (21–25). To illustrate this internal workflow from data entry to block formation and chain construction, a schematic representation of the technical pipeline governing blockchain operation has been represented in Fig. 3.

Blockchain types and platforms

Building upon this core architectural foundation, the blockchain networks can be classified according to their access models and the operational governance into three fundamental types such as, the public, private and consortium blockchains. The public (permissionless) blockchains, such as bitcoin, ethereum etc., are very open to all participants and emphasise the transparency, censorship resistance and decentralised control, allowing anyone to read, write or validate the transactions. Then, the private (permissioned) blockchains are controlled by a single organisation, restricting the access to approved participants and thereby, providing enhanced privacy, security and the tailored governance, suitable for enterprise

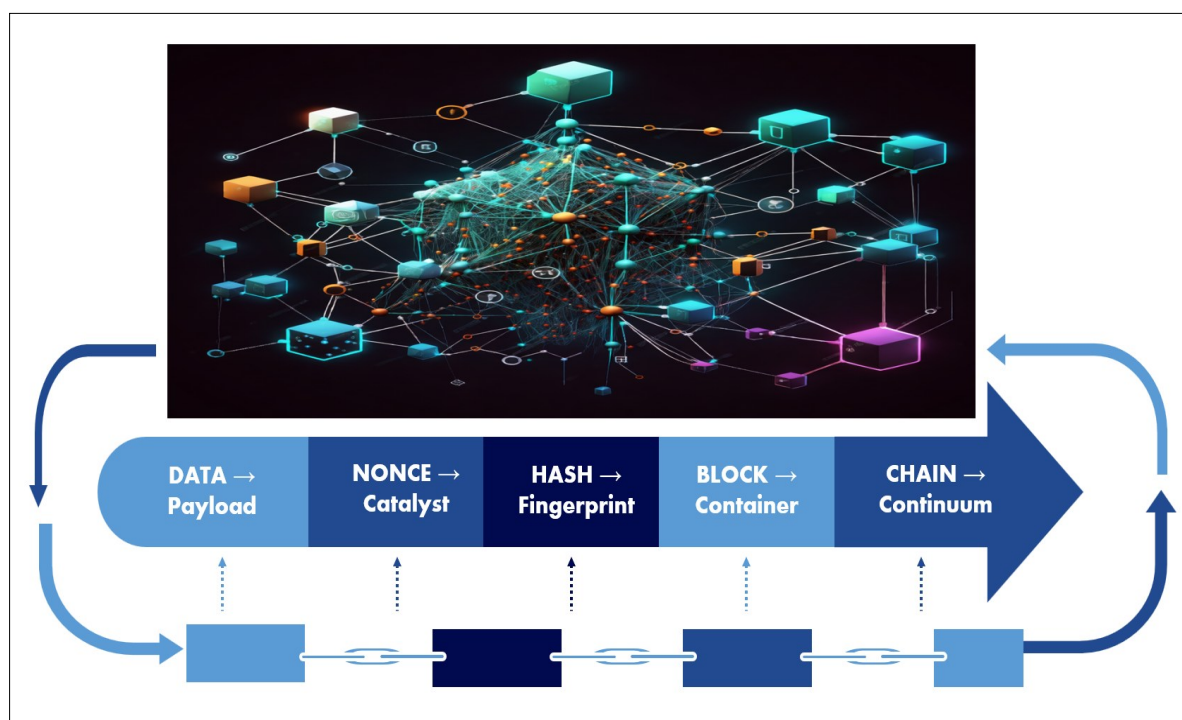


Fig. 3. Inside the chain: Technical flow of blockchain architecture.

or internal applications. The consortium blockchains, another form of the permissioned blockchain, were managed jointly by a group of organisations. Access is limited to all of the authorised members, while governance responsibilities were shared among the consortium participants, making them ideal for collaborative networks across each industry or supply chains. Building upon these access models, the smart contracts were self-executing scripts that are embedded within the blockchain, automate transactions and business logic without human intervention, thereby reducing the operational friction and the errors. To efficiently manage large datasets namely, images or videos, blockchain often store only cryptographic hashes on-chain, while the original data resides in decentralised file systems such as the inter planetary file system (IPFS), ensuring both scalability and the verifiability (26–32). To visualise these of the blockchain types, a schematic overview of the public, private and consortium networks and their operational characteristics are illustrated in Fig. 4.

Global domains of application

Since blockchain technology was originally developed to enable the secure, decentralised cryptocurrency transactions. Its innovative core architecture provides the trust, immutability and transparency and quickly demonstrated potential beyond the digital currencies. Recognising this transformative capability, multiple sectors began to implement the blockchain technology to improve the trust, security, accountability and for operational efficiency. In the financial industry, blockchain has transformed the payments, remittances and capital markets by facilitating the disintermediation, programmable assets and the faster settlements. In the supply chain and logistics operations, blockchain enables the end-to-end traceability, provenance verification, and real-time auditing, enhancing trust and efficiency in the global trade. In the healthcare, blockchain has been employed to protect interoperable patient records, prevent counterfeit medicines and thereby ensure transparency in drug supply chains. In agriculture sector, blockchain facilitates the farm to fork traceability, fair-trade verification and the transparent subsidy distribution, empowering both producers and consumers while promoting accountability across the food systems. The convergence of blockchain with IoT and the smart systems has enabled secure, verifiable and automated operations across the decentralised sensor networks and the autonomous devices. Government and administrative sectors have adopted blockchain for transparent voting systems, digital identity management, land

registries and the anti-corruption initiatives, thereby strengthening civic trust and accountability. The energy sector is also leveraging the blockchain technology for the peer-to-peer energy trading, decentralised grid management and the renewable certificate tracking, promoting sustainability and democratising access. From its inception as a cryptocurrency enabler, blockchain has evolved into a cross-domain transformative technology, transforming industries by embedding decentralisation, immutability and the consensus into diverse global systems (33–37). To visualise this widespread adoption of blockchain across multiple sectors, a schematic representation of the leading domains that have embraced blockchain technology, highlighting the flow from its origin in cryptocurrency to transformative applications in finance, supply chain, healthcare, IoT and smart systems and public governance are represented in Fig. 5.

Blockchain in agriculture: Pioneering food traceability

In the year 2017, Walmart, one of the world's largest food retailers, had conducted a pioneering experiment using the blockchain technology to track the pork products in China and the results were revolutionary. This innovation had reduced the time required for the traceability from several days to mere seconds, enabling real-time transparency at every stage of the food supply chain, from farm to processor to retailer. This milestone not only created a new international benchmark for the supply chain integrity but also showed the immense potential of the blockchain technology to transform the entire agricultural systems. Following this landmark initiative, the global interest in agricultural blockchain applications has surged. Today, the blockchain is being implemented for the food safety monitoring, certification verification, index-based crop insurance, supply chain automation and smart contracts to validate the authenticity of every input and product origin. By dismantling the traditional information silos and overcoming the fraudulent practices, blockchain technology is enhancing the traceability, transparency and the trust across agricultural-based value chains, encompassing crops, livestock and processed foods (38). This evolution marks a paradigm shift, positioning the blockchain as a critical enabler of secure, resilient and digitally empowered agricultural ecosystems. To represent this evolution, the integration of blockchain technology across the agricultural value chains, highlighting its transformative role in enabling the real-time traceability, transparency and trust from farm to fork has been illustrated in Fig. 6.

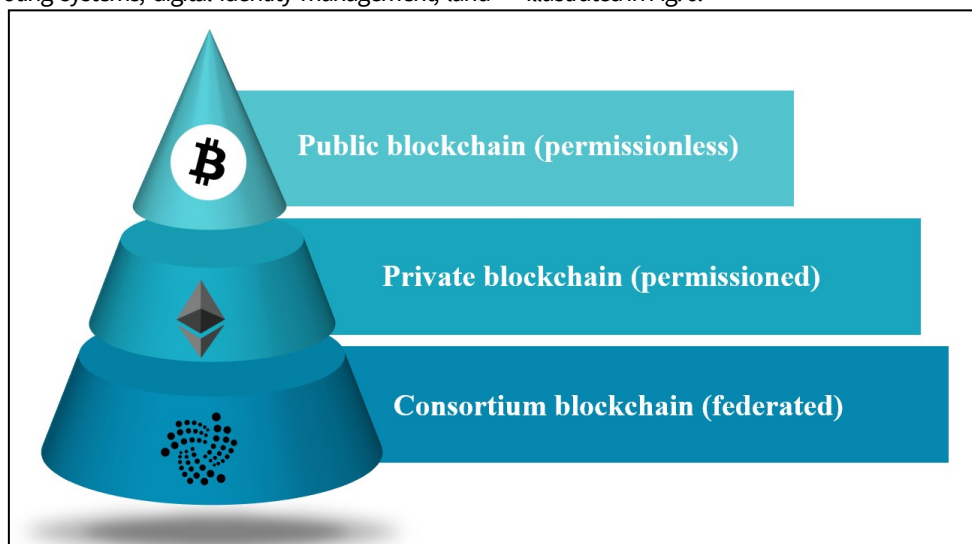


Fig. 4. Spectrum of blockchain networks: Public, private and consortium architectures.

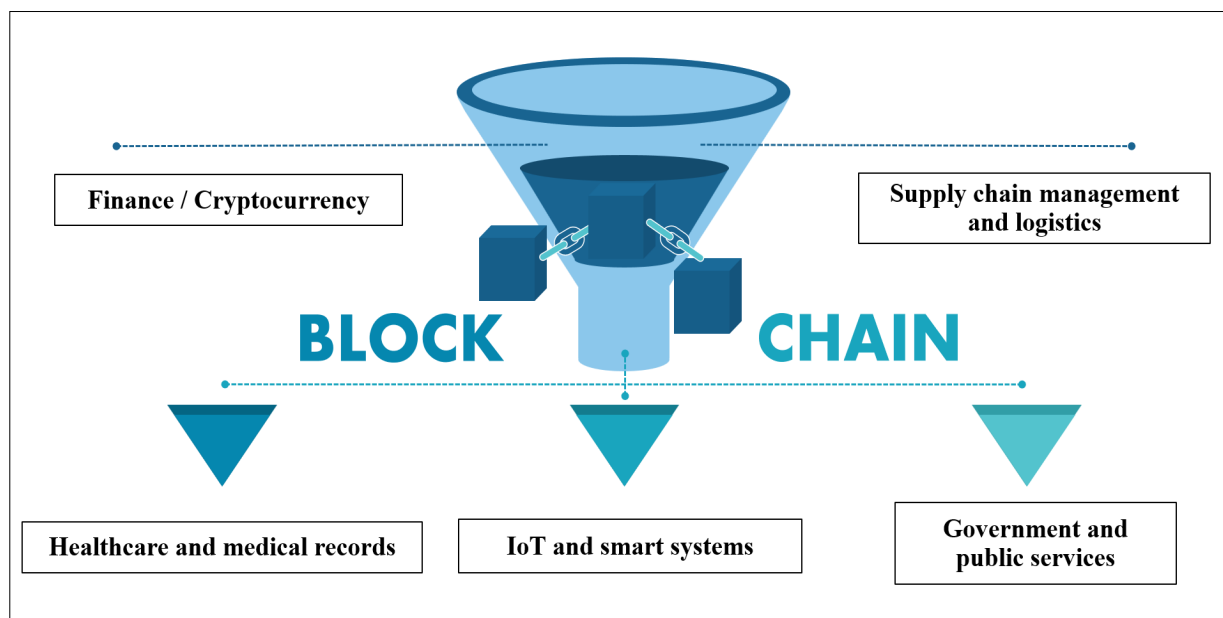


Fig. 5. Blockchain adoption across leading global domains: From cryptocurrency to cross-sectoral transformation.

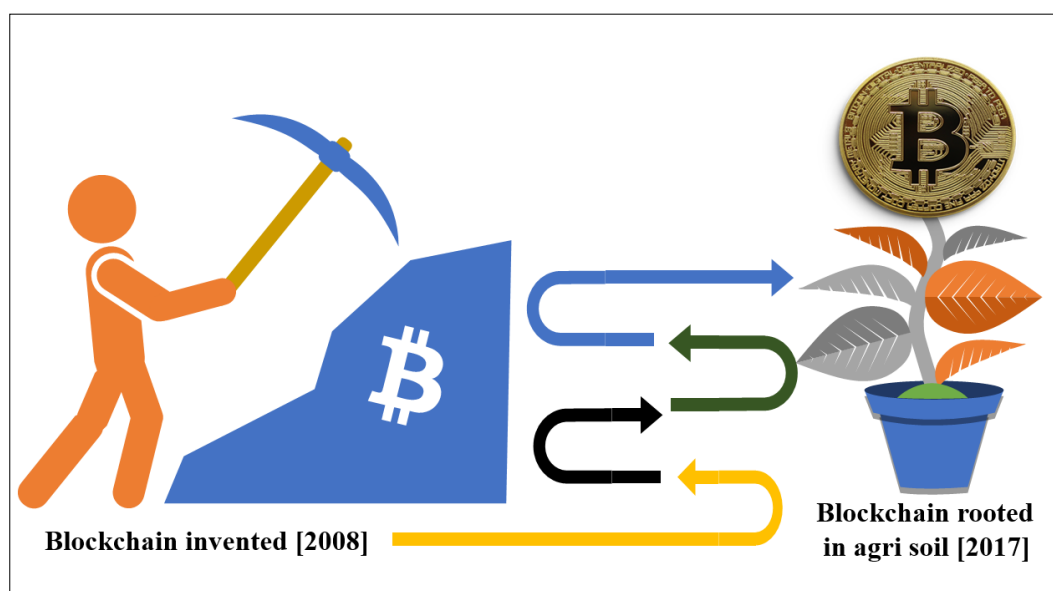


Fig. 6. From farm to fork: Blockchain-enabled food traceability in agriculture.

Blockchain protocols in agriculture

In the agriculture sector, a blockchain protocol refers to a well-defined set of rules and procedures that governs how the agricultural data is captured, authenticated, recorded and shared among the stakeholders across the value chain. These protocols integrate technological advances in the IoT devices, smart contracts and the decentralised storage, to create a secure and transparent framework for the end-to-end data governance in agricultural-food systems (39, 40). By establishing how the data is captured, authenticated, transmitted, validated and accessed, these protocols enhance the traceability, integrity and the accountability throughout the agricultural lifecycle, from farm to final consumption.

Data acquisition and origin authentication

At the initial stage of the agricultural lifecycle, the IoT-enabled sensors and microcontrollers, namely, Arduino and Raspberry Pi, collect the granular, real-time data during the seed selection and planting stages. The core parameters include a unique identifier, the geolocation, seed variety and the sowing date, which are important for the provenance verification and the regulatory compliance.

These collected data points were transmitted through the secure protocols to the blockchain network and to the decentralised storage systems, namely, IPFS, ensuring a tamper-resistance and the machine-verifiable records. This technological framework ensures the transparency while overcoming the risks of data manipulation inherent in the traditional centralised systems (41–45).

Blockchain platform selection for agri-traceability

Selecting a suitable blockchain platform is very pivotal for an effective agricultural-traceability. The permissioned blockchain platforms, including the Hyperledger Fabric and the Quorum, were favoured for the enterprise and consortium applications because of their privacy controls, scalability and modular consensus mechanisms. The public blockchains, such as ethereum, provide an open, auditable supply chains and smart contract ecosystem. Platforms namely, Sawtooth and Multi Chain, offer a modularity and a customisable permission, allowing tailored implementations for a various agricultural context. The platform choice is mainly guided by the factors namely, privacy requirements, interoperability, scalability and the extent of the smart contract integration required (46).

Smart contracts and automated data governance

Smart contracts form the fundamental architecture of the automated governance in today's modern agricultural blockchain systems. By encoding the business logic directly on-chain, these smart contracts validate the incoming agricultural data, enforce access controls and automate the compliance checks, minimising the human error and the operational inefficiencies. This integration with the decentralised storage platforms namely, IPFS addresses the limitations of the large, heterogeneous datasets, comprising the sensor logs, the images and the videos, thereby enabling the system resilience and transparency (47, 48).

Harvest data logging and validation

At the harvest period, the critical information namely, yield, date of harvest, the moisture content and multimedia evidence is collected and then recorded on-chain and in the decentralised storage. Smart contracts automatically authenticate these entries, digitise assets and facilitate transparent market access, making an automated quality certification while reducing the risk of fraudulent reporting. This convey that stakeholders, from farmers to regulators, have been access to a verifiable, real-time information, strengthening the trust throughout the supply value chain (49).

Market transactions and asset exchange

Blockchain redefine the agricultural market operations by providing a transparent, auditable bidding and asset transfer mechanisms. The verified buyers can transact directly with the producers, minimising intermediary involvement and the market asymmetry. This facilitates fair pricing and also maintains a tamper-proof record of all the transactions, supporting dispute resolution, financial incorporation and the empowerment of the smallholder farmers (50).

Post-harvest logistics and chain of custody

The post-harvest processes, such as storage, transportation and handling, were meticulously tracked on chain. Each of this custody operation is immutably recorded, facilitation a complete traceability and rapid product recall in the event of safety breaches or disputes. The advanced privacy-preserving protocols, namely, zero-knowledge proofs (example., ZK-STARKs), can be combined to ensure that the sensitive business data remains secured and confidential while maintaining the transparency of the chain of custody.

Consumer verification and trust interface

At the consumer level, this blockchain technology facilitate an end-user to instantly verify a product's origin, safety and the sustainability credentials by scanning the QR codes on packaging. This capability empowers an informed purchasing decision, ensuring brand trust and the incentivises sustainable practices throughout the agricultural-value chain, representing a hallmark of the next generation, digitally empowered agricultural-food traceability systems (51).

Major blockchain applications in agriculture

Organic product certification

Blockchain provides an immutable record of organic farming practices, ensuring that products labelled as "organic" truly meet the required standards. By tracking inputs that were used during the entire cultivation, it prevents the fraudulent labelling of conventional produce. This builds significant trust with premium consumers who

are willing to pay more for verified organic goods. The system allows for real-time auditing by certification bodies, reducing the time and cost of manual inspections. It creates a transparent history that protects both honest farmers and health-conscious consumers (52).

Animal husbandry and livestock tracking

In livestock management, blockchain monitors the health, vaccination history and movement of animals to prevent the spread of diseases. Each animal can be given a digital identity document (ID) that records its lineage, feed types and medical treatments on a shared ledger (53). This is critical for managing outbreaks like foot and mouth disease, as it allows for precise tracing of infected animals. Furthermore, it ensures the quality of dairy and meat products by verifying the living conditions of the livestock. Such systems enhance the value of animal products in international markets that demand high welfare standards.

Land registration and titling

Blockchain is used to create tamper-proof land registries, which are essential for protecting the property rights of smallholder farmers. By recording land titles on a decentralised ledger, the risk of data manipulation and fraudulent land grabs is significantly reduced (54). This transparency makes it easier for farmers to use their land as collateral for securing bank loans. Many governments are adopting this to replace antiquated, paper-based systems that are prone to corruption. It ensures a clear, undisputed history of ownership that facilitates smoother land transactions.

Agricultural insurance

Smart contracts on the blockchain can automate insurance payouts based on weather data, such as rainfall or temperature levels (55). When a predefined weather event occurs, the contract automatically triggers a payment to the farmer without the need for manual claims processing. This eliminates the "human factor" and potential corruption in damage assessments, making the process faster and more transparent. For small farmers, this provides a critical safety net against climate change-induced weather extremes. It reduces the administrative burden on insurance companies while providing immediate financial relief to affected producers.

Supply chain trade finance

Blockchain facilitates faster and more secure payments between farmers, distributors and retailers by reducing reliance on traditional banking intermediaries (56). Smart contracts can ensure that a farmer is paid immediately upon the digital verification of delivery at a warehouse.

Smart farming and internet of things integration

Blockchain serves as a secure backbone for IoT-driven smart farming, where sensors collect data on soil moisture, crop growth and weather (57). By recording sensor data on an immutable ledger, farmers can ensure the accuracy of their datasets for precision agriculture. This data-driven approach helps in optimising the use of water and fertilisers, leading to higher productivity and sustainability.

Food authentication and provenance

This application focuses on preventing food fraud by verifying the origin and authenticity of high-value products like wine, honey, or specialty coffee (58). Blockchain creates a "digital twin" for each batch, documenting its journey through every processing and packaging stage. This makes it nearly impossible for counterfeiters to inject fake products into the legitimate supply chain.

National agri-food blockchain pilot projects

Coffee board of India blockchain marketplace

The Coffee Board of India launched a blockchain-based marketplace in collaboration with Eka software solutions to provide better price discovery for small coffee growers. This pilot project allows farmers to trade their produce directly with buyers, reducing the influence of intermediaries. It provides full traceability of Indian coffee, allowing stakeholders to verify the origin and quality of the beans (59). The project has helped in streamlining documentation and improving efficiency for small exporters.

Andhra Pradesh land registry pilot

The state of Andhra Pradesh partnered with companies like Zebi Data and ChromaWay to digitise land records using blockchain technology (60). This initiative aimed to prevent the widespread issue of land record tampering and fraudulent transactions in rural areas. By creating a “civil supplies registry”, the state ensured that public aids and land titles were stored securely against cyber-attacks. While the pilot showed success in data security, challenges remained regarding the large-scale migration of old paper records. It remains a benchmark for using decentralised ledgers for government services in India.

Telangana blockchain district and land records

Telangana established a “blockchain district” in Hyderabad and implemented a pilot for digitising land records and government services (61). The state signed multiple memorandum of understanding (MoUs) with technology companies to improve transparency in government to citizen services. This project focused on creating a secure ecosystem for data management and preventing corruption in rural administration. A key lesson learned was the importance of public-private partnerships in driving technology adoption. Success stories include faster verification processes for land transfers, though scalability across all districts is an ongoing goal.

Madhya Pradesh land record management

A pilot project in Madhya Pradesh focused on the technical implementation of blockchain for managing rural land records. This project aimed to provide citizens with a decentralised database that ensures the privacy and integrity of their land holdings. It addressed the need for encrypted, tamper-proof systems in regions where property disputes are common. However, the pilot faced challenges such as slow transaction speeds and the high resource intensity of the blockchain system (62). This highlighted the need for more efficient consensus mechanisms in large-scale government applications.

Tamil Nadu (Annamalai University, Faculty of Agriculture, Chidambaram): A simulated farm-level pilot validation of blockchain implementation in cotton farming

The study was conducted at Experimental farm, Department of Agronomy, Faculty of Agriculture, Annamalai University, Chidambaram, where a traceability prototype was developed for the agronomic phase of the cotton value chain using a 0.5-acre hybrid cotton field. The entire agronomic operations from sowing to harvest, along with weather data and crop observations, were digitally recorded, supported by geo-referenced images and integrated into a dynamic QR code enabling plot-level, chronological traceability. The findings reveal that even without IoT integration or full blockchain deployment, QR-based digital records can provide a

practical and farmer-friendly traceability solution for smallholder systems. This approach enhances transparency, documentation and data discipline, while serving as a transitional model toward full blockchain adoption. Future implementation would involve migrating these records to a permissioned blockchain with secure storage systems such as IPFS, ensuring data integrity and end to end traceability across the cotton value chain (7, 63).

Real-world implementations of blockchain in agriculture

To visualise the practical implementation of blockchain technologies in the agricultural sector, Table 1 summarises the adoption and implementations of blockchain-based systems in agriculture, highlighting their core objectives, application domains and underlying the technological platforms. These examples illustrate how the distributed ledger technologies are being integrated with farming, agricultural-food supply chains, financial services and the smart agriculture to enable traceability, data security and operational efficiency. This table has been adapted and conceptually restructured to ensure the clarity and originality (64).

Adoption barriers in developing countries

The adoption of blockchain in developing countries faces significant hurdles, primarily centred on cost and infrastructure. Implementing these systems is economically inaccessible for many small-scale agricultural enterprises that lack the capital to invest in high-tech research and development. In rural environments, the effectiveness of blockchain is hampered by a lack of robust internet connectivity, which is crucial for real-time data transmission and transparency (65). Furthermore, a massive “digital gap” exists; many smallholders lack the computer skills and digital literacy required to interact with complex blockchain interfaces. In countries like India, the majority of farmers have small landholdings and find it difficult to enter data in English or operate smartphones, which are not universally available. Beyond technical issues, there is a shortage of skilled blockchain developers; for instance, India was estimated to have only 5000 skilled developers out of a total of 2 million. The lack of awareness among farmers about the benefits of blockchain also leads to low trust and slow adoption rates (66). Additionally, the high energy consumption and computing requirements of some blockchain systems make them difficult to maintain in regions with unstable power supplies.

Research gaps

Current research is limited by a lack of large-scale, long-term implementations that demonstrate the technology's viability beyond small pilot projects. There is a critical need for interoperable systems that allow different blockchain platforms to communicate across various segments of the food supply chain. Future research must also focus on reducing the high computational energy costs and improving the scalability of decentralised ledgers for high-volume agricultural transactions.

Future direction (part 3): Crypto transactions in agriculture

Future research will explore the integration of cryptocurrency and stable coins for cross-border agricultural trade. This could bypass traditional banking barriers for small exporters and reduce transaction delays. Research is needed to develop secure, low-volatility crypto-payment systems that can function in low-connectivity rural areas, ensuring that farmers receive fair and immediate compensation for their produce.

Table 1. Representative blockchain-based systems applied in contemporary agricultural practices

Use case/system	Functional objective	Application domain	Blockchain framework
Walmart food tracking pilot	Records and verifies the production and movement of pork and mangoes throughout the retail chain	Product traceability	Hyperledger Fabric
Egg distribution monitoring system	Tracks egg movement from farms to consumers within regional supply networks	Product traceability	Hyperledger Sawtooth
Brazilian grain export platform	Supports export logistics by digitally certifying grain trade transactions	Product traceability	Hyperledger Fabric
Grape certification verification	Authenticates quality and export certificates for grape shipments from Africa to Europe	Product traceability	Hyperledger Fabric
E-commerce food tracking solution	Provides blockchain-based certification and monitoring of online food transactions	Product traceability	Hyperledger Fabric
EPCIS-based food traceability model	Integrates blockchain with EPCIS standards to ensure reliable traceability	Product traceability	Ethereum
Secure product transaction system	Evaluates blockchain-based deployment for product traceability and security	Product traceability	Ethereum
OriginChain platform	Identifies and verifies the provenance of agricultural products	Product traceability	Ethereum
RFID-enabled cold-chain tracking	Uses RFID sensors and blockchain to monitor refrigerated supply chains	Product traceability	Ethereum
AgriBlockIoT	Stores and validates IoT sensor data across agricultural supply networks	Product traceability	Hyperledger Sawtooth and Ethereum
Intelligent irrigation control system	Applies blockchain to regulate irrigation and minimise water wastage	Smart agriculture	Ethereum
Blockchain-assisted watering framework	Combines fuzzy logic and blockchain to enhance irrigation reliability	Smart agriculture	Custom (Java-based)
Aquaculture monitoring network	Secures data collected from fish farms using blockchain technology	Smart agriculture	Hyperledger Fabric
Robotic swarm farming model	Coordinates distributed agricultural robots via blockchain-based decision making	Smart agriculture	Multichain
IoT data sharing framework	Enables secure information exchange from accelerated simulation datasets	Smart agriculture	Corda
Soybean trading platform	Records and completes commercial soybean transactions using blockchain	Agricultural finance	Ethereum
Food trade consortium network	Implements consortium blockchain for regional food trade operations	Agricultural finance	Ethereum
State farm insurance model	Manages agricultural insurance data through blockchain automation	Agricultural finance	Quorum
AgriDigital grain payment system	Automates post-harvest payments and transaction settlement for farmers	Finance and traceability	Quorum

Conclusion

In part 1, we unveiled how the big data has transformed agriculture from the passive record-keeping to a real-time, predictive intelligence system, enabling smart farming and data-driven decision-making. Yet, as reliance on the digital insights grows, the data without trust and security becomes a critical vulnerability. Building on this foundation, part 2 demonstrates that blockchain technology offers the missing pillar such as, a decentralised, tamper-proof framework that ensures the transparency, verifiability and end to end traceability across the agricultural-value chain. By integrating internet of things (IoT), smart contracts and secure data management, blockchain not only safeguards and secure the integrity of agricultural data but also empowers farmers, enhances the consumer trust and strengthens the sustainability and regulatory compliance. Together, these two technological epochs, big data intelligence and blockchain-enabled trust, chart a transformative path toward resilient, transparent and equitable agriculture for the digital age.

Thus, digital agriculture, driven by the twin technological giants of big data and blockchain, does not end with these advancements, yet it still faces critical research gaps, particularly in large-scale validation, interoperability and system scalability. Extending this trajectory, part 3 will explore how addressing these challenges, along with the potential of cryptocurrency and stablecoin-based transactions, can enable faster, more transparent and inclusive agricultural trade.

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Authors' contributions

TP conceptualised, structured and drafted the manuscript. PS provided visionary guidance, introduced the study domain and critically revised the manuscript. His innovative vision for the agricultural domain and steadfast support has been pivotal in navigating the complexities of this technological frontier, ultimately shaping this review. This work, culminating in a multi-part review series, stands as a reflection of his cognitive vision. SR, MM, PB and KAD contributed through insightful discussions. All authors reviewed, revised and approved the final manuscript.

Compliance with ethical standards

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