

## Blockchain-Based Food Supply Chain Traceability: A Systematic Review of Privacy Preserving and Scalability

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### Abstract

Food is fundamental to human survival, we eat to live, sustaining ourselves with nutrition that meets our daily needs. Food security, defined as universal physical and financial access to safe and nutritious food, depends heavily on efficient supply chains. However, ensuring this security faces significant challenges in tracking and transparency. This study examines two critical problems in blockchain-based food supply chain tracing: privacy preservation and scalability. While blockchain technology combined with Internet of Things (IoT) devices offers promising solutions for real-time monitoring, transparency, and fraud prevention in agricultural supply chains, questions remain about balancing computational efficiency with privacy protection, achieving scalable integration across multi-actor supply chains without compromising traceability, and implementing these systems in resource limited environments. Through a comprehensive review of current research, this study identifies emerging technologies like Zero Knowledge Proofs (ZKPs) and ZK-Rollups that enhance both throughput and privacy in decentralised systems. The research presents layered architectural models integrating blockchain ledgers, off-chain storage, IoT sensors, and cryptographic protocols to enable secure and scalable traceability. These models support compliance verification while protecting sensitive data and can be adapted for low-resource contexts. The findings demonstrate that scalable, privacy-preserving blockchain technologies can transform agricultural traceability, empowering supply chain stakeholders while maintaining data confidentiality and integrity. The study also identifies future research needs, including cross-chain interoperability, policy integration, cost-benefit analysis for smallholder farmers, and field validation.

**Keywords:** Blockchain, Food Supply Chain, Traceability, Privacy Preservation and Scalability.

### 1.0 Introduction

Food is essential to human survival, no man on the planet could survive without food, no matter how small it might be, we eat food to live, we don't live to eat food. When there is physical and financial access to enough safe, nourishing food to meet everyone's needs for a healthy existence, that is food security. We therefore depend solemnly on food security. However, a number of factors, including the supply chain, have a significant impact on food security.

Supply chains nowadays are becoming more intricate, dispersed, and data-driven. Food fraud, food contamination, infrastructure, drug counterfeiting, data manipulation, and lack of transparency are among the problems that traditional systems face. Problems significantly impair global supply chains' security and transparency [1] Traceability becomes important in order to address the numerous concerns that are emerging. Food traceability has grown in significance as worries about safety, quality, and transparency in global supply chains have increased, claim [2] Modern food logistics cannot use traditional traceability systems since they are frequently centralised and susceptible to manipulation. In food networks, blockchain technology is presented as a decentralised, impenetrable solution that can improve data integrity and trust.

The supply chain, a dispersed system that includes all the operations involved in moving different agricultural products from producers to final customers, is a major factor in determining the economic development of the country. However, there isn't a system in place in the agriculture sector right now to verify and monitor the distribution of seeds and food crops (Agro-Information System) [3]. This means that farmers are unable to get accurate information about where the seeds they want to purchase and plant come from.

[4], opined that more dependable traceability solutions are required as a result of the rise in the frequency and complexity of food safety issues. Conventional food safety traceability systems frequently depend on centralised databases, which are opaque and susceptible to manipulation. A decentralised, unchangeable solution provided by blockchain technology can improve responsibility and trust in food supply systems. But the openness and transparency of blockchain also give rise to worries about data privacy, particularly when private data is at stake. With a variety of distribution channels and global vendors, modern supply chains are becoming more and more complicated. Because traditional systems frequently use enclosed databases, it can be challenging to confirm product origins and guarantee traceability [5], [6].

Blockchain is one of the most fascinating and contentious research subjects in the realm of technology these days. A Japanese person or group of Japanese people by the name Satoshi Nakamoto introduced blockchain technology to the banking industry for the first time in 2008. Smart contract technology was incorporated into the blockchain to increase its robotic capabilities. This gave the transaction a unique and reliable protocol [6]. Blockchain is economically driven technology because of its features [7]. Blockchain is an authentic digital database that was made possible by technology [8]. Blockchain is a digital database of economic transactions that is impenetrable and can be configured to record almost anything of value, not only financial transactions. For this reason, the value of each people fluctuates and depends on their application viewpoints. Fast, dependable transactions are made possible by blockchain, a distributed, decentralised database of records that is not monitored by centralised management [9].

[10] said Blockchain technology is considered as a way to improve food safety systems' traceability, data integrity, and trust. [5] also agreed that the decentralised, unchangeable blockchain technology is presented as a way to improve food supply chains' accountability and traceability. The report highlights how blockchain may enhance data integrity, lower fraud, and make it easier to comply with food safety laws. Foodborne illnesses and the intricacy of contemporary food supply chains, which make it challenging to promptly identify the sources of contamination, are additional global concerns[11].

It is now challenging to guarantee food authenticity, safety, and sustainability due to the introduction of multiple actors like cross-border logistics, and fragmented data brought about by the globalisation of food systems[12]. To trace the food on transits it is only departed time and arrival time can be taken but what happened in between can not be traced which is another problem to be addressed especially in underdeveloped countries.

Therefore, security in traceability of food remains challenging as mentioned in[12], [13], [14] and scalability on the side of the blockchain are all challenging facing in food traceability as mentioned in [15], [16], [17] Base on the following gaps identified in the literature this review is conducted based on the following major research questions.

1. What are the best ways to balance computational efficiency and privacy protection in blockchain-based food traceability systems?
2. What architectural approaches, without sacrificing traceability or data integrity, can provide scalable blockchain integration in multi-actor food supply chains?
3. What are the effects of IoT integration on blockchain privacy and scalability of agricultural food supply chains in settings with limited infrastructure?

In a recent review by [1] stated that with the immutable records, transparent data flows, and tamper-resistant transaction logs, blockchain technology has demonstrated a great deal of promise in addressing some supply chain traceability issues. But for blockchain to be used effectively in actual supply chains, architectural design and technical constraints like scalability, interoperability, and privacy must be carefully considered. The paper thoroughly analyses current blockchain-based supply chain solutions, categorising them according to their storage mechanisms, cryptographic underpinnings, and structural models. It pays particular attention to understudied humanitarian logistics scenarios. It presents a three-dimensional evaluation framework for comparing various architectural approaches in terms of security, traceability, and integrity. Still there is need to address the scalability and privacy preservation.

Similarly, [12], stated that the intrinsic openness and immutability of blockchain technology can improve traceability, reduce food fraud, and boost customer confidence, changing how information systems are implemented in the Food Supply Chain environment. However, issues including scalability, data quality, integration complexity, and regulatory considerations need to be solved. Also suggested that Artificial Intelligence (AI) integration would be a viable solution to these problems, which will enhanced Blockchain be a stronger solution for food safety and fraud protection by this combination, which can also successfully address some current challenges such guaranteeing data accuracy and system compatibility.

Furthermore, [14] Reveal that blockchain technology allows for real-time tracking, minimises food waste, and ensures food safety, it has the potential to improve the food supply chain's transparency, efficiency, and sustainability. Utilising bibliometric analysis, it was discovered that the research community is expanding and that international cooperation is necessary to advance the area and exchange knowledge. The study included several recommendations for future research, including scalability, consumer education, security, standardisation, and interdisciplinary cooperation for future research on food supply chain and traceability. Table 1 lists the main distinctions between this review article and other previous review studies on food supply chain traceability in terms of their contributions.

. This review aims to address three core research questions: What are the best ways to balance computational efficiency and privacy protection in blockchain-based food traceability systems? What architectural approaches, without sacrificing traceability or data integrity, can provide scalable blockchain

integration in multi-actor food supply chains? What are the effects of IoT integration on blockchain privacy and scalability of agricultural food supply chains in settings with limited infrastructure?

Table 1: Comparative analysis of the current study and relevant review studies

Paper Author(s)	Main Areas	Focus Development Generalization	& Technology Covered	Key Contributions	Emerging Technology
[1]	Security, traceability, integrity in general supply chains	Broad generalization across industries; emphasis on evolving systemic demands	Blockchain, smart contracts, IoT	Synthesizes blockchain's role in securing supply chains and improving data integrity	Integration of AI predictive analytics with blockchain
[12]	Food safety, digital transformation, traceability	Sector-specific generalization; emphasis on transformation stages	Blockchain, smart contracts, cloud platforms	Maps blockchain's role across food supply chain stages; identifies barriers to adoption	Blockchain–AI convergence for predictive food safety
[14]	Food supply chain, bibliometric trends, research gaps	Maps academic landscape; identifies collaboration networks and citation clusters	Blockchain, smart contracts	Visualizes research trends; identifies dominant themes and underrepresented regions	Blockchain–twin integration for real-time monitoring
This Paper	Traceability, Scalability and Privacy-Preserving	Generalized with modular, privacy-preserving components agriculture	IoT-Blockchain, scalable, IoT Device, Off-chain for Storage	Layered scalability, applications agriculture roadmap	models, Zero Knowledge Proof (ZKP), ZK Rollup

**1.1 Information Sources and Search Strategy**

This research follows established systematic literature review protocols in computer science as outlined by [18] to ensure comprehensive examination. A methodical search was conducted across five major open-access journal repositories to identify relevant studies on privacy-preserving and scalability in blockchain-based food supply chain traceability. The selected repositories and their URLs are presented in Table 2 below:

Table 2: Journal repositories and their URLs

Journal Repository	URL
IEEE Xplore	<a href="https://ieeexplore.ieee.org/">https://ieeexplore.ieee.org/</a>
SpringerLink	<a href="https://link.springer.com/">https://link.springer.com/</a>
Elsevier	<a href="https://www.elsevier.com/">https://www.elsevier.com/</a>
MDPI	<a href="https://www.mdpi.com/">https://www.mdpi.com/</a>
Google Schola	<a href="https://scholar.google.com/">https://scholar.google.com/</a>

The search was conducted using the following search strings: "blockchain AND food supply chain AND traceability," "blockchain AND agriculture AND privacy," "blockchain AND food traceability AND scalability," "IoT AND blockchain AND food security," and "zero-knowledge proof AND supply chain." The search covered publications from January 2019 to December 2025, focusing on the period when blockchain adoption in agricultural supply chains gained significant momentum.

**2.0 Literature review**

The body of literature examining blockchain based traceability in food supply chains which has expanded considerably, driven by growing concerns surrounding food safety, authenticity, and transparency. As global

supply chains become increasingly complex, conventional tracking systems frequently struggle to ensure data integrity and provide real time visibility. Blockchain technology presents a promising solution by facilitating decentralised, tamperproof recordkeeping across multiple stakeholders.

### 2.1 Deficiency in Supply Chain

As seen in Figure 1, traceability in supply chain entail tracking goods through a number of phases, starting with production and continuing through warehousing and logistics, distribution and transportation, processing, or points of sale, and finally arriving at the customer. However, when items cannot be sufficiently monitored from raw ingredients to completed goods, a lack of traceability becomes a serious problem. This condition causes a number of issues, including losses during the distribution phases, opaque production procedures, and the difficulty to confirm the product's provenance. The main causes of the lack of traceability are specifically variations in data formats and management systems among stakeholders, the lack of standardised data representation techniques, and deficiencies in trustworthy data storage mechanisms[19].



Figure 1: Security issues in supply chain

### 2.2 Traceability Focused Research

The blockchain based food traceability system demonstrates how food products move from farmers to end consumers, as depicted in Figure 2. It highlights internal traceability across every stage of the supply chain production, processing, distribution, retailing, and final consumption. The model also shows the supporting technologies and standards involved in this process, including product labeling systems and web-based traceability platforms. In addition, the diagram embeds a food safety and quality framework that progresses through GMP/GHP, HACCP, ISO certifications, and Total Quality Management (TQM).

Recent literature reinforces the effectiveness of such systems in real-world applications. [16] developed ShrimpChain, a blockchain-based framework for Bangladesh's shrimp export industry, demonstrating how transparent and traceable supply chain mechanisms can enhance product credibility and export potential. Their system successfully addressed authentication challenges and information asymmetry between producers and international buyers, showing that blockchain can bridge trust gaps in agricultural exports. Similarly, addressing scalability concerns that often limit blockchain adoption in large-scale supply chains, [20] proposed a hypergraph-based data sharding approach for enterprise blockchain storage. Their work tackles the computational and storage bottlenecks that emerge when handling high-volume transactional data, offering a solution that maintains data integrity while improving system throughput. Overall, the illustration aligns with contemporary academic models that promote decentralised, transparent, and secure tracking mechanisms in food supply chains, reflecting global efforts to strengthen safety, accountability, and consumer confidence through technological innovation [21].

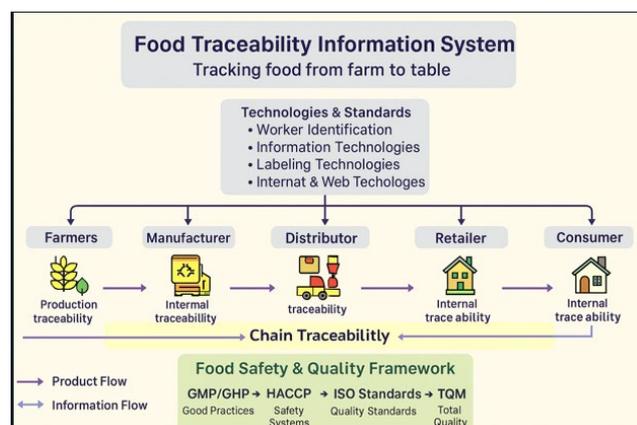


Figure 2: Food Traceability information system

The four studies in Table 3 highlighted how crucial traceability is becoming to food supply chains, and they all tackle the problem from different technological and disciplinary angles. [22] concentrate on the legal and organisational requirements for blockchain implementation in supply chains for dairy products. Through qualitative case studies, they pinpoint 18 prerequisites that must be met for blockchain to be adopted successfully, ranging from standardisation and governance to interoperability and trust. Without institutional alignment, technological preparation alone is insufficient, as the work highlights. Using a technical method, [23] test the effectiveness of RFID tags on various kinds of packaged meat through experiments. Particularly for UHF and NFC technology, their research shows how meat composition and packaging shape impact tag readability. They recommend blockchain as an additional tool for safe data management, although their research mostly focusses on whether item-level identification is physically feasible, leaving consumer applications and blockchain integration untested.

A conceptual framework named ShrimpChain is put up by [16] to address the problems of traceability and transparency in Bangladesh's shrimp export sector. To track shrimp from hatchery to export, their hybrid blockchain platform combines smart contracts, IoT sensors, and a certification system that is based on scores. Although the framework is intended to empower farmers and enhance the quality of their products, it is still theoretical and has not been empirically validated or implemented in the real world. [24] offer a cutting-edge system for digitising food product data and improving traceability that integrates blockchain, explainable AI (XAI), QR codes, and deep learning (Faster RCNN). With this method, customers can use QR codes to check nutritional information and identify potentially dangerous items. Despite its innovation, the framework is not field tested and ignores stakeholder integration and regulatory compliance.

Table 3: Analysis of research on traceability

Authors	Traceability Focus	Methodology	Technologies Discussed	Key Contributions	Limitations / Gaps
[22]	Organizational and regulatory boundary conditions for traceability in dairy food supply chains	Case study analysis using 16 interviews across four supply chains	Blockchain (permissioned), traceability standards (GS1, EPCIS)	Identified 18 boundary conditions for blockchain-based traceability; emphasized need for standardization and governance	No technical implementation or performance testing of blockchain systems
[16]	End-to-end traceability in shrimp supply chain to improve export quality	Conceptual framework design with hybrid blockchain and IoT integration	Blockchain (Ethereum, Corda), IoT, IPFS, smart contracts, QR codes	Proposed ShrimpChain with score-based certification and community consensus for data authentication	No real-world deployment or empirical validation; scalability and regulatory integration not tested
[23]	Item-level traceability of meat products using RFID	Experimental trials with UHF and NFC tags on four meat types	RFID (UHF, NFC), dual-frequency tags, blockchain (conceptual)	Benchmarked tag performance across packaging types and meat compositions; proposed RFID-blockchain integration	No blockchain implementation; consumer-facing applications remain conceptual
[24]	Digitized traceability and food safety verification using QR codes and AI	Technical framework integrating deep learning, blockchain, and QR code	Blockchain (ECIES), XAI-Faster RCNN, QR codes, cloud computing	Developed a secure food recommendation system with explainable AI and encrypted traceability	No field testing or stakeholder validation; limited discussion on regulatory compliance

These studies demonstrate how organizational preparedness, technical innovation, and stakeholder engagement must all come together for traceability privacy preservation to be effective. The other studies suggest and evaluate a range of technological options, from RFID and IoT to AI and smart contracts, while Behnke & Janssen emphasize the fundamental requirements for blockchain adoption. The lack of extensive application and interaction with current regulatory frameworks, however, unites all four. In order to close these gaps, future studies should combine user-centred design, policy alignment, and empirical validation.

### 2.3 Scalability in Blockchain

The problem of scalability in blockchain systems is complex and calls for creative architecture at the application, network, data, and consensus layers. The interrelated architectural elements that help address the complex problem of blockchain scalability are depicted in Figure 3 below. The necessity to increase transaction throughput, lower latency, and preserve data integrity across various applications is at the heart of this difficulty.

Different architectural approaches offer varying trade-offs between performance and complexity. [20] proposed HyperShard, which intelligently distributes transactions among shards using hypergraph-based data partitioning. By balancing storage demands and reducing cross-shard communication, this method significantly improves enterprise IT system performance with relatively modest computational overhead since the partitioning logic operates independently of transaction validation. In contrast, [25] emphasize how AI namely machine learning and deep learning can improve consensus processes, identify weaknesses, and protect privacy. However, their AI enhanced consensus algorithms introduce substantially higher computational overhead due to continuous model training and inference operations. While [25]'s approach offers adaptive optimization and anomaly detection capabilities that sharding alone cannot provide, it demands more powerful hardware and energy resources, making it less suitable for resource constrained environments. The key distinction lies in where processing burden is placed: HyperShard distributes existing workload more efficiently, whereas AI enhanced consensus adds intelligent processing layers that increase total computational demand while improving decision quality.

In food supply chains, [16] introduced ShrimpChain, a hybrid blockchain-IoT system that permits decentralised traceability across different participants. This system demonstrates how blockchain can be horizontally scaled while preserving transparency using smart contracts and sensor data. [23] highlight the importance of RFID technology in obtaining item level data from the standpoint of physical infrastructure, which is necessary for incorporating blockchain into logistics and retail settings. Additionally, [24] demonstrate how intelligent data processing can support scalable applications in public health by proposing a consumer facing paradigm that integrates blockchain with explainable AI and QR codes to validate food safety in real time.

Collectively, these strategies illustrated in Figure 3 show that blockchain scalability requires coordinated innovation across consensus algorithms, data structures, IoT connectivity, physical infrastructure, and intelligent interfaces rather than a single solution. While each solution makes the ecosystem more resilient and scalable, there remains a gap in practical implementation and comparative performance evaluation under real-world conditions, which emphasizes the need for more empirical research examining these approaches across different deployment scenarios.

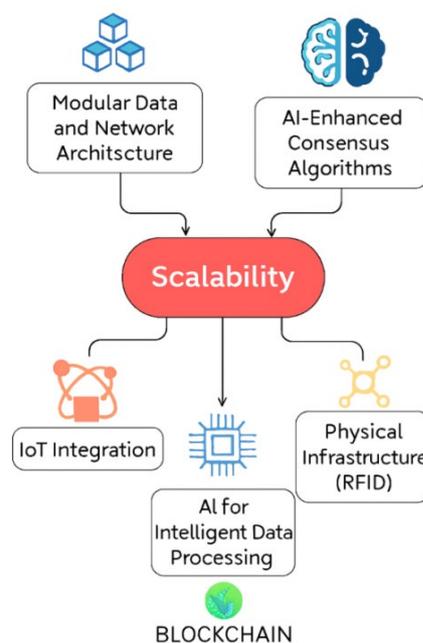


Figure 3: Typology of scalability in Blockchain

### 2.4 IoT integration on Blockchain Privacy and Scalability

Figure 4 shows how IoT integration improves blockchain scalability and privacy in agricultural food supply chains, especially in environments with inadequate infrastructure. Regarding privacy, real-time food product monitoring is made possible by IoT devices like RFID tags, GPS trackers, and wireless sensors, which record vital environmental data like temperature, humidity, and location. This data creates a tamper proof record that

improves transparency while protecting sensitive information when it is safely transferred and stored on a blockchain[26] support this mechanism, emphasizing that IoT enabled blockchain systems can reduce fraud and increase stakeholder trust. Additionally, identity free verification is made possible by the incorporation of zero-knowledge proofs (ZKPs), as discussed by [27] This is particularly useful in decentralised networks where privacy concerns may discourage participation, since it allows farmers and suppliers to demonstrate compliance with standards like organic certification or regional origin without disclosing private or proprietary information.

However, implementing these technologies in settings with limited infrastructure presents significant energy cost challenges. IoT sensors require continuous power for data collection and transmission, which can be problematic in rural areas with unreliable electricity grids or where solar-powered solutions are the only viable option. The energy demands multiply when these devices must maintain constant connectivity to blockchain networks. Furthermore, cryptographic operations required for blockchain validation and ZKP computations are computationally intensive, consuming substantial processing power that may exceed the capacity of low-cost hardware typically deployed in resource constrained environments.

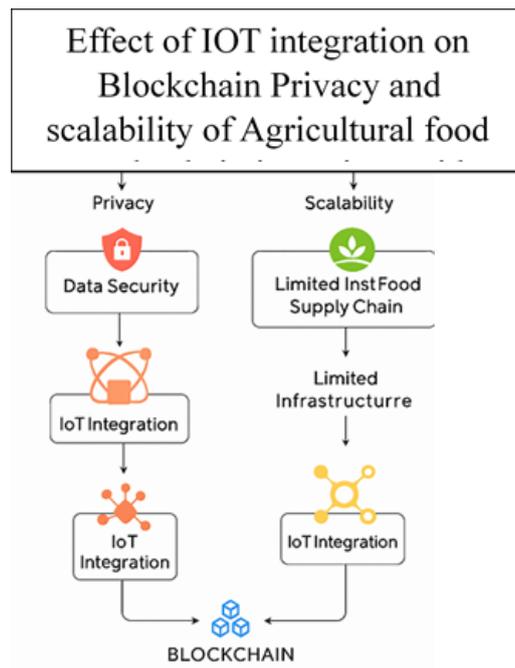


Figure 4: Integration of IoT in Blockchain

Regarding scalability, IoT integration reduces manual labour and permits real-time traceability even in rural or resource-constrained situations by automating data collecting across farms, warehouses, and distribution centres. In order to enable agricultural actors to engage in a scalable digital ecosystem, [28] suggest a five-stage structure that includes IoT setup, secure data transmission, blockchain storage, frontend development, and deployment. Their concept demonstrates that modular IoT and blockchain integration may get around infrastructure constraints, even in the face of obstacles like connectivity issues and energy expenses. This is further supported by [29], who highlights ZK-Rollups, which combine several transactions off-chain and use brief proofs to validate them on-chain. Because of the significant improvement in throughput and decrease in computing burden, blockchain systems are now more feasible in areas with limited bandwidth. These studies collectively demonstrate that blockchain applications in agriculture that are both scalable and privacy-preserving are accelerated by IoT connectivity.

## 2.5 Zero Knowledge Proof (ZKP) and ZK-Rollups

Scalability and privacy preservation are two of the most important issues in blockchain-based agricultural systems, and Figure 5 shows a tiered architecture that directly solves these issues. These problems are particularly noticeable in environments with inadequate infrastructure, where there are restrictions on energy, bandwidth, and data security. Real-time data gathering and location metrics that are crucial for food traceability are accessed through IoT devices. However, the blockchain would become overloaded if all of this raw data were stored directly on it, which would result in expensive and delayed operations. It can be fixed using off-chain storage, which maintains blockchain efficiency by offloading large amounts of data to systems like IPFS or cloud databases. [26] who contend that IoT-blockchain integration improves traceability while lowering data fragmentation and centralisation, endorse this strategy.

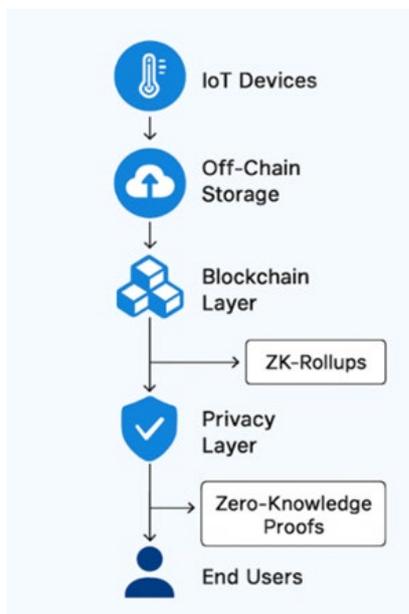


Figure 5: Layered Architecture for Scalable and Privacy-Preserving Integration of IoT

The system is anchored by the blockchain layer, which ensures immutability and transparency by storing hashed references and metadata. This is further scaled by including ZK-Rollups, a technique that submits a single concise proof on-chain while batching many transactions off-chain. This lowers gas fee and significantly boosts throughput up to 2000x, according to [29], making blockchain feasible even in areas with limited bandwidth.

Access control and encryption are managed by a separate privacy layer, which protects privacy. This is further supported by Zero-Knowledge Proofs (ZKPs), which enable stakeholders to confirm compliance (such as ethical sourcing or organic certification) without disclosing private information. according to [27] A crucial component of decentralised networks where data disclosure may pose hazards to competition or regulations is identity-free verification, which ZKPs make possible.

Lastly, the system is securely used by end users, regulators, and supply chain partners, who can access certified data without jeopardising privacy. This architecture offers a workable solution to the blockchain trilemma in agriculture: simultaneously attaining decentralisation, scalability, and privacy. It also scales effectively while protecting sensitive data.

## 2.6 Future research

1. **Field Validation in Agricultural Environments with Limited Infrastructure.** To evaluate the practical performance of IoT-blockchain systems in resource-constrained or rural settings, conduct pilot studies. This entails assessing blockchain throughput, sensor dependability, and connectivity resilience in situations with constrained energy and bandwidth.
2. **Evaluation of Cost-Benefit for Adoption by Smallholders.** Examine whether implementing scalable and privacy-preserving blockchain systems for small-scale farmers is financially feasible. Particularly in developing nations, research should evaluate initial expenditures, long-term savings, and return on investment.
3. **Frameworks for Regulation and Policy for ZKP-Enabled Traceability.** Examine how national and international food safety rules can incorporate zero-knowledge proofs. Creating guidelines for data governance and privacy-preserving compliance verification in decentralised supply chains.
4. **Models of Interoperability Among Blockchain Networks.** Create and evaluate cross-chain verification procedures that enable the safe exchange of traceable information between various blockchain systems. Without sacrificing privacy, this would promote international supply chains and increase openness.

## 2.7 Conclusion

In this systematic research, the dual problems of scalability and data confidentiality in agricultural food supply chains were investigated in relation to blockchain-based traceability systems, when combined with IoT and privacy-preserving technology. According to recent research, IoT devices make it possible to collect data in real time, and ZK-Rollups and off-chain storage greatly lower blockchain congestion and increase throughput. Zero-knowledge proofs (ZKPs) give stakeholders the ability to confirm compliance without disclosing private information, which further improves privacy. The conceptual models created for this review provide useful answers for low-infrastructure settings by demonstrating how different technologies interact across layered

systems. All things considered, the results confirm that blockchain systems can facilitate safe, scalable, and transparent food tracking when they are carefully constructed. However, for these frameworks to be widely adopted, more empirical support and policy congruence are required. This review lays the groundwork for further study and application in supply chain governance and digital agriculture.

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