IoT–Blockchain Integration for Smart Agriculture: A Systematic Review of Architectures, Applications, Benchmarking, and Open Challenges

Senthil Kumar V Aneesh
School of Computer Science and Engineering, VIT-AP University, Amaravati, Andhra Pradesh, India
ORCID ID: 0009-0008-1758-2904

ABSTRACT

IoT-blockchain convergence has the potential to improve smart agriculture by supporting immutable provenance chains, cryptographic data integrity, and decentralized trust mechanisms across agricultural value networks. This systematic review examines integrated system architectures, communication protocols, consensus frameworks, and applications including supply chain provenance tracking, precision agriculture, crop monitoring, and parametric insurance. [1] The literature suggests an architectural migration from centralized cloud models toward edge-distributed and multi-ledger topologies designed to mitigate consensus latency, throughput constraints, interoperability gaps, and energy overhead. Blockchain is commonly used as a trust and auditability layer in many proposed systems, recording transactions and executing smart contract logic, while IoT sensor networks provide distributed field-scale biophysical measurements. The review indicates the need for standardized evaluation criteria for throughput, latency, energy consumption, and reporting transparency, identifying persistent deficits: field-validated implementations, privacy-preserving mechanisms, and technology accessibility for smallholder communities. Future trajectories align with Agriculture 5.0 paradigms, prioritizing edge-embedded intelligence, energy-efficient consensus protocols, and inclusive deployment architectures that accommodate heterogeneous stakeholder capabilities.[16]

Keywords: Internet of Things (IoT), Blockchain, Smart Agriculture, Supply Chain Traceability, Precision Farming, Artificial Intelligence, Smart Contracts, Agriculture 5.0, Food Security.

INTRODUCTION

1.1 Motivation and Scope

Global agriculture is under growing pressure as rapid population growth continues to strain production capacity. This shift has created an urgent need for systems that can improve efficiency, transparency, and resilience across fragmented supply chains. Conventional farming models still rely heavily on manual crop monitoring, paper-based records, and reactive decision-making. As a result, they struggle to cope with climate variability, declining soil and water resources, and structural inefficiencies in supply chains. These limitations often lead to significant post-harvest losses, a higher risk of food fraud, and delayed responses to environmental stress. The integration of Internet of Things (IoT) and blockchain technologies provides a practical way to address these challenges. Distributed sensor networks enable continuous, real-time monitoring of environmental conditions and crop behaviour. At the same time, blockchain offers a tamper-resistant ledger that supports secure data sharing, ensures transaction integrity, and enables end-to-end supply chain traceability. [1] This review examines the rapidly evolving research landscape from 2022 to 2026, bringing together studies covering system architectures, communication frameworks, application domains, implementation challenges, and emerging research directions in IoT-blockchain-enabled agricultural systems. [16]

1.2 Research Objective

This review offers a systematic and critical synthesis of IoT-blockchain integration architectures and operational frameworks in smart agriculture. It examines system design topologies and layered communication protocol stacks in detail, and outlines key application areas, including supply chain traceability, variable-rate precision farming, and parametric crop insurance models. The study further evaluates the role of machine learning inference, edge-based artificial intelligence, and connectivity technologies such as 5G and LPWAN. These components contribute to improving system scalability, responsiveness, and overall resilience. [2] In addition, the analysis addresses practical implementation challenges, including issues related to technical interoperability, regulatory inconsistencies, and limited stakeholder adoption. It also highlights emerging research directions that aim to support long-term sustainability and enhance the resilience of modern food systems. [5]

1.3 Background and Problem Context

Smart agriculture integrates advanced information and communication technologies to improve crop productivity, optimize resource utilization, and ensure transparent supply chain governance. Within this framework, IoT sensor networks collect diverse data, including crop growth patterns, soil moisture and nutrient levels, local microclimate conditions, and livestock health indicators. These heterogeneous data streams are transmitted through LPWAN protocols, 5G networks, or hybrid communication models to edge computing nodes or centralized cloud platforms. [3] Blockchain complements these systems by addressing key limitations of standalone IoT architectures. It enables tamper-resistant and cryptographically secured transaction records that support reliable audit trails. Smart contracts, particularly those built on Ethereum-compatible platforms, encode automated conditional processes such as releasing payments upon verified delivery events or triggering insurance payouts after validated crop damage assessments, reducing reliance on intermediaries and minimizing delays. Together, this integrated architecture establishes IoT as the sensing and data acquisition layer, while blockchain functions as the trust and verification backbone, enabling secure data provenance, transparent operations, and controlled access across multiple stakeholders. [13]

1.4 Contributions

This paper makes the following contributions:

- Systematic synthesis of peer-reviewed studies published between 2022 and 2026, selected through a structured multi-database search and screening process.
- A standardized benchmarking framework for evaluating IoT-blockchain agricultural systems across throughput, latency, energy consumption, and auditability dimensions.
- Comparative analysis across IoT-only, blockchain-only, and integrated system architectures, spanning supply chain traceability, precision agriculture, and parametric insurance.
- Identification of persistent research gaps including the absence of large-scale field validation, insufficient privacy-preserving mechanisms, and limited accessibility for smallholder farmers.

REVIEW METHODOLOGY

This systematic review was conducted in accordance with structured literature review principles to ensure reproducibility, comprehensiveness, and methodological transparency. The following subsections describe the database selection, search strategy, and paper selection process applied to identify the corpus of studies analyzed in this work.

2.1 Databases and Search Strategy

The literature search was conducted across the following academic databases: IEEE Xplore, Scopus, ScienceDirect (Elsevier), SpringerLink, MDPI Open Access Journals, and Frontiers in Research. These databases were selected based on their comprehensive coverage of engineering, computer science, agricultural technology, and interdisciplinary research relevant to IoT and blockchain systems. The search was restricted to peer-reviewed publications from January 2022 to March 2026 to capture recent and emerging developments.

The following primary and secondary keyword combinations were used in the search queries:

- IoT agriculture, Internet of Things smart farming, IoT crop monitoring
- Blockchain agriculture, blockchain food supply chain, distributed ledger agriculture
- IoT blockchain integration agriculture, smart contracts farming

- Precision agriculture sensor network, LPWAN agriculture, 5G agriculture
- Parametric crop insurance blockchain, traceability food chain IoT
- Agriculture 5.0, edge computing agriculture, federated learning smart farming

Boolean operators (AND, OR) were applied to combine primary domain terms with application-specific qualifiers to maximize retrieval coverage while minimizing irrelevant results.

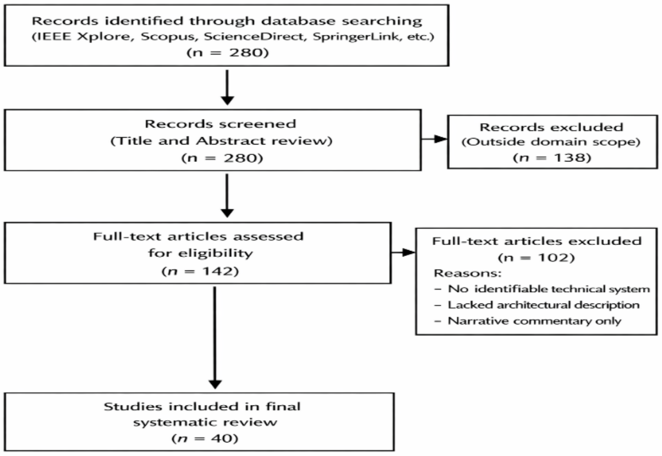
2.2 Inclusion and Exclusion Criteria

The inclusion criteria were defined as follows:
(i) Peer-reviewed journal articles, conference proceedings, or book chapters;
(ii) Studies with a primary focus on IoT, blockchain, or their integration within agricultural or food supply chain contexts;
(iii) Publications in the English language;
(iv) Studies proposing, implementing, or evaluating a technical system, framework, or architecture; and
(v) Publications within the defined 2022–2026 time window.

The exclusion criteria were applied to remove:
(i) Studies not written in English;
(ii) Grey literature, technical reports, and non-peer-reviewed preprints without associated journal or conference publications;
(iii) Studies focusing exclusively on unrelated domains such as healthcare or logistics with no agricultural application;
(iv) Duplicate publications where the same system was reported multiple times; and
(v) Papers for which the full text was unavailable through institutional access.

2.3 Paper Selection Process and PRISMA-Style Flow

The selection process followed a four-phase approach consistent with systematic review methodology. In the Identification phase, a total of 280 candidate records were retrieved across all six databases using the defined keyword combinations.In the Screening phase, titles and abstracts were reviewed to exclude records that were not relevant to IoT–blockchain applications in agriculture, resulting in 142 records proceeding to full-text review. In the Eligibility phase, full-text articles were assessed against the predefined inclusion and exclusion criteria, considering domain relevance, methodological rigor, and reporting clarity. Studies were excluded if they did not present a clearly identifiable technical system, lacked sufficient architectural detail, focused on non-agricultural domains, or consisted solely of narrative discussion without empirical or evaluative content.In the Inclusion phase, 40 studies were retained as the final analytical corpus. These studies encompass IoT-based agricultural systems, blockchain-based agricultural applications, and integrated IoT–blockchain deployments, and form the basis for the comparative analysis, benchmarking framework, and research gap identification presented in this review.



LITERATURE REVIEW

3.1 IoT-Based Systems in Smart Agriculture

Recent research in IoT-enabled agriculture (2022-2026) shows strong progress in automated environmental monitoring, adaptive irrigation control, plant stress detection, and yield prediction models. Most studies follow a three-layer architecture consisting of the perception layer (sensor devices), the network layer (communication protocols), and the application layer (data analytics and user interfaces). Hybrid communication models that combine LPWAN and 5G technologies are increasingly used to balance coverage, latency, and energy efficiency across geographically distributed farms. [6] Despite these developments, standalone IoT systems still face practical limitations. Common issues include weak endpoint authentication, poor interoperability across heterogeneous platforms, and limited battery capacity in remote deployments. These constraints reduce long-term reliability and highlight the need for additional security and system support mechanisms. [17]

3.2 Blockchain-Based Systems in Smart Agriculture

Blockchain applications in agriculture mainly focus on improving supply chain traceability and ensuring food safety by creating transparent and tamper-resistant records across distributed stakeholder networks. These systems rely on the immutability of distributed ledgers to track product movement from farm to consumer, improving accountability and trust. [4] Smart contracts further support automation by enabling transactions without intermediaries. However, the choice of consensus mechanisms introduces trade-offs, especially in energy consumption and scalability. Adoption remains limited, particularly among smallholder farmers who often lack the required infrastructure. In addition, many proposed systems are still tested in simulation environments rather than validated in real agricultural conditions. [12]

3.3 Integrated IoT-Blockchain Systems

The integration of IoT and blockchain has become a rapidly growing research area, offering a combined approach to data collection and trust management in agriculture. In these systems, data generated by IoT sensors are hashed and recorded on blockchain networks, creating secure and verifiable data provenance trails that resist tampering. [2] everal studies indicate a shift toward from centralized cloud-based systems to edge-enabled distributed models, reducing latency and network load while improving system responsiveness. Advanced approaches explore multi-ledger frameworks to address scalability issues and use reinforcement learning techniques to optimize precision farming based on trusted sensor data. [11] However, several challenges remain unresolved, including protocol-level latency, the need for privacy-preserving mechanisms for sensitive agricultural data, and the limited availability of large-scale field deployments to validate these systems beyond controlled environments. [20]

TECHNOLOGIES OVERVIEW

4.1 Internet of Things in Agriculture

The Internet of Things (IoT) represents a distributed ecosystem of interconnected devices that combine sensors, actuators, and communication modules to enable continuous data collection and machine-to-machine interaction with minimal human involvement. In agricultural environments, the perception layer captures key parameters such as soil composition, moisture levels, environmental conditions, crop health indicators, and livestock physiological data, while actuators enable automated operations like precision irrigation and nutrient application. [1] The network layer selects appropriate communication protocols, including LPWAN, 5G, or hybrid configurations, based on coverage requirements, data transmission needs, and energy constraints common in large-scale farming. The application layer integrates edge computing and cloud-based platforms to support real-time data processing, advanced analytics, and coordinated decision-making, allowing more responsive and adaptive farm management. [6]

4.2 Blockchain Technology

Blockchain technology provides a decentralized ledger system that records transactions in a sequence of cryptographically linked blocks across a peer-to-peer network. Each block includes verified transaction data, a hash of the previous block, and timestamp information, ensuring data integrity and resistance to unauthorized changes. Proof-of-Work consensus mechanisms offer strong security through computational effort but often result in high energy consumption, while alternatives such as Proof-of-Stake and delegated models improve efficiency with lower resource usage. Permissioned blockchain platforms, such as Hyperledger Fabric, use Practical Byzantine Fault Tolerance to achieve higher scalability and throughput, making them suitable for enterprise-level agricultural applications. [12] Smart contracts further enhance functionality by encoding conditional rules that automate processes like payment release after delivery verification, supply chain tracking, and insurance claim settlement without relying on centralized intermediaries. [3]

IOT AND BLOCKCHAIN INTEGRATION

5.1 Integration Architecture

IoT-blockchain integration defines a layered architecture in which agricultural field data, collected through distributed sensor networks, is securely processed and recorded within immutable ledger systems. A commonly used five-tier model operates as follows: sensor nodes capture soil parameters, environmental conditions, and crop-related data; edge gateways handle data filtering, compression, and cryptographic hashing to reduce transmission load and latency; the blockchain layer records transaction hashes as immutable entries managed by smart contracts; the analytics layer applies machine learning methods for pattern recognition and time-based analysis; and the presentation layer provides verified insights to stakeholders such as farmers, insurers, consumers, and regulatory authorities. [11] To address storage and scalability challenges associated with on-chain data, most systems adopt hybrid architectures that store only cryptographic hashes on the blockchain while keeping complete datasets in distributed off-chain storage solutions such as IPFS or similar decentralized platforms.

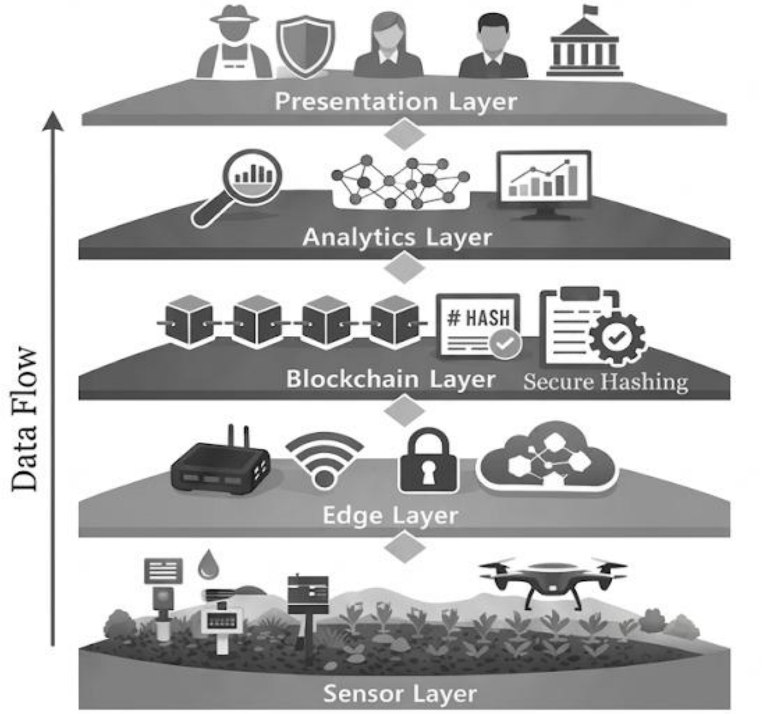


Figure 1 illustrates the five-tier IoT–blockchain integration architecture described above.

5.2 Key Applications

Supply chain traceability remains the most established application of IoT-blockchain integration. Sensor-generated data including harvest records, cold-chain temperature logs, transportation routes, and ownership transfers is recorded on-chain to ensure transparency and accountability across the supply network. [13] Precision agriculture systems use smart contracts to automate field-level operations such as irrigation scheduling, fertilizer application, and pest control based on real-time sensor data and predefined thresholds. Parametric crop insurance is another important application, where IoT-based environmental indicators including soil moisture, vegetation indices, and temperature data trigger automated claim settlements through blockchain contracts, reducing delays and administrative effort. Decentralized agricultural marketplaces further extend these capabilities by combining IoT-based product quality verification with blockchain-enabled payment and escrow systems, supporting direct transactions between producers and buyers, reducing dependency on intermediaries, and improving overall transaction efficiency. [12]

COMPARATIVE ANALYSIS

This section presents a structured comparison of the reviewed studies across IoT-based, blockchain-based, and integrated IoT-blockchain systems. The tables below use distinct rows, explicit reporting labels, and only the technical details stated in the manuscript or directly inferable from the cited study titles.

TABLE I

Comparison of IoT-Based Agricultural Systems

Study / Focus	Application Area	Communication Protocol	Architecture	Reported Strength	Reported Limitation
IoT in Agriculture (2025)	Multi-domain monitoring	LoRaWAN	Distributed	Broad use-case coverage	No security layer
IoT and AI in Agriculture (2025)	Crop monitoring	NB-IoT	Centralized	High prediction accuracy	High energy consumption
Reliable IoT Connectivity (2025)	Connectivity optimization	LPWAN	Hybrid	Balanced latency	High deployment cost
AI and IoT Crop Monitoring (2024)	Precision irrigation	ZigBee	Centralized	Reported water reduction	Limited scalability
Sustainable and Precision Agriculture (2024)	Livestock and agroforestry	5G	Distributed	Multi-domain integration	Complex management
Secured Triad IoT + ML (2025)	Crop forecasting	LoRa	Edge-based	Improved forecast accuracy	Requires ML expertise

Analysis of IoT-focused studies shows that hybrid LPWAN and 5G architectures tend to outperform single-protocol deployments in balancing energy efficiency and latency. Earlier research is largely based on centralized designs, while more recent work increasingly adopts distributed and edge-based approaches. Research attention remains concentrated on precision irrigation and crop monitoring, whereas livestock monitoring and agroforestry receive comparatively less focus. A major limitation persists across IoT-based systems: robust, built-in security mechanisms are often missing.

TABLE II
Study-Level Extraction Matrix for Blockchain-Focused Agricultural Systems

Study	Primary Focus	Blockchain Role	Technical Detail	Metric Reported	Reporting Note
[3] Synergizing IoT, AI, and Blockchain	Smart agriculture	Integrated pipeline	The study notes the need for edge-deployable models	NR	Qualitative analysis; no quantitative performance metrics reported.
[8] Modernizing Agriculture with Real-Time Crop Insurance	Crop insurance	Smart contract automation	Settlement reduced from weeks to hours	Time to settlement	Measured in temporal units (reduction from weeks to hours).
[12] Exploring IoT-Blockchain Integration in Agriculture	Experimental integration	On-chain hashing of IoT data	Shift from centralized to edge-enabled designs	NR	Evaluates architectural shift qualitatively; lacks standardized benchmarking.
[15] Blockchain Framework for Certification of Organic Agriculture Production	Organic certification	Certification framework	Certification workflow for organic agriculture	NR	Proposes a conceptual workflow; no empirical measurements provided.
[18] Adaptation of IoT with Blockchain in Food Supply Chain Management	Food supply chain	Traceability and provenance	Improves traceability and lowers fraud risk	NR	Qualitatively assesses fraud risk reduction; lacks measurable data.
[20] Agriculture-Food Supply Chain Management Based on Blockchain and IoT	Supply chain interoperability	Enterprise blockchain interoperability	Narrative on interoperability across stakeholders	NR	Narrative analysis; no quantitative metrics extracted.
[2] Smart Agriculture 5.0: Blockchain and Reinforcement Learning Synergy	Multicropping optimization	RL-embedded blockchain pipeline	Autonomous multicropping scheduling with audit traceability	NR	Demonstrates system capabilities; lacks quantitative benchmarking data.

The matrix above lists distinct studies and only the technical details explicitly present in the manuscript. Where a study-level metric was not stated in the source text, the table uses NR (not reported) instead of estimating a value.

TABLE III
Agricultural Challenge-to-Solution Mapping

Agricultural Challenge	Why It Matters	IoT-Blockchain Response Pattern	Evidence in Manuscript
Water scarcity	Requires timely irrigation decisions	Soil sensing + edge analytics + smart contract-guided irrigation	Discussed in precision farming and future directions
Soil degradation	Needs continuous monitoring and restoration	Sensor networks + ML + auditable records	Covered in IoT-based monitoring sections
Supply chain fraud	Reduces trust in provenance records	Blockchain traceability + immutable logs + off-chain data hashes	Covered in traceability discussion
Latency in field operations	Real-time actions can be delayed by consensus	Edge/fog preprocessing + permissioned ledgers	Identified as a key challenge
Digital literacy barriers	Limits adoption by smallholder farmers	User-centered design and simplified onboarding	Highlighted in challenges and future work
Privacy in multi-stakeholder sharing	Farm data can reveal sensitive operational details	Zero-knowledge proofs or privacy-preserving access control	Discussed as promising but computationally heavy

TABLE IV
Cross-Domain Comparison of IoT-Only, Blockchain-Only, and Integrated Systems

Dimension	IoT-Only	Blockchain-Only	Integrated
Data security	Low	High	Very high
Real-time performance	High	Low	Moderate
Transparency	Low	High	Very high
Scalability	Moderate	Low to moderate	Moderate
Energy efficiency	Moderate	Low to high depending on consensus	Moderate
Implementation cost	Low to moderate	High	High
Adoption readiness	Moderate	Low	Low to moderate
Automation capability	Moderate	High	Very high

6.1 Standardized Benchmarking Criteria

Because the reviewed studies report heterogeneous outputs, this review standardizes comparison using a common reporting rule. Throughput is interpreted as transactions per second or an equivalent processing rate; latency is interpreted as end-to-end delay or consensus time; energy consumption is grouped as low, medium, or high based on the computational burden of the sensing and consensus layer; and scalability is assessed by the ability to handle additional nodes, sensors, or transactions without collapse of service quality. When a paper does not report a metric directly, the review records it as NR rather than estimating a value.

TABLE V
Benchmarking Variables Used for Cross-Study Comparison

Metric	Operational Definition	Suggested Proxy	Reporting Rule
Throughput	Number of valid transactions or updates processed per second	TPS or equivalent system update rate	Report numeric value if available; otherwise, NR
Latency	Time from sensing event to verified record or action	Consensus delay or end-to-end delay in seconds	Report measured value or range
Energy consumption	Computational and communication energy burden	Low / medium / high by consensus and network type	State the basis of classification
Node count	Number of devices or ledger participants in the testbed	Sensor nodes, edge nodes, or blockchain peers	Report exact count where possible
Storage strategy	How data are stored and validated	On-chain / off-chain / hybrid	Describe whether hashes or payloads are stored on-chain
Auditability	Ease of tracing a record from source to decision	Binary or ordinal assessment supported by architecture	Explain the audit path in text

6.2 Key Observations and Research Gaps

The comparative synthesis highlights five key observations. Edge-enabled blockchain architectures show strong potential for scalable agricultural deployments. Energy-efficient consensus mechanisms, such as Proof-of-Stake and delegated Byzantine Fault Tolerance, are essential for ensuring environmental sustainability. Smart contract execution provides measurable efficiency improvements in areas such as insurance processing, supply chain validation, and automated resource management. Advanced privacy-preserving techniques, including zero-knowledge proofs, offer significant theoretical benefits but are not yet mature for practical agricultural use. In addition, much of the existing literature relies heavily on simulations or small-scale pilot studies, which limits broader applicability and external validation. [7] Several research gaps still remain. There is a lack of standardized benchmarking frameworks for evaluating system performance. Regulatory alignment across regions is also insufficiently addressed. Accessibility challenges for smallholder farmers receive limited attention, despite their importance for real-world adoption. Furthermore, there is a clear shortage of long-term field studies that capture complete agricultural cycles and seasonal variations.

CHALLENGES AND ISSUES

IoT-blockchain integration in smart agriculture faces several technical, economic, and operational challenges that limit its large-scale deployment. Scalability remains a key concern, as agricultural IoT networks can involve thousands of distributed sensor nodes, while many blockchain platforms—particularly those based on legacy proof-of-work—offer limited transaction throughput, typically around 7-15 transactions per second, resulting in processing bottlenecks. [6]

Financial constraints also restrict adoption, especially for smallholder farmers. The combined costs of sensors, edge devices, blockchain infrastructure, and transaction fees often exceed available resources. Energy consumption presents another major challenge, as agricultural systems depend on low-power devices, while some consensus mechanisms require high computational energy, making them unsuitable for battery-operated or solar-powered environments.

Latency introduced by consensus validation further complicates real-time agricultural operations. In addition, security and privacy concerns remain significant. IoT devices are vulnerable to physical tampering, and advanced cryptographic techniques such as homomorphic encryption and differential privacy introduce additional computational overhead, which can further impact overall system performance. [20]

FUTURE RESEARCH

Future research should move beyond conceptual integration approaches and focus on developing rigorous and comparable evaluation frameworks under standardized agricultural conditions. For low-power sensing environments, LPWAN technologies such as LoRaWAN and NB-IoT need systematic benchmarking against 5G networks using consistent variables, including crop types, terrain conditions, and seasonal variations. Similarly, permissioned blockchain platforms like Hyperledger Fabric should be evaluated alongside public blockchain systems using common metrics such as payload size, node distribution, and end-to-end latency performance. Time-sensitive agricultural operations, including irrigation control and pest detection, should prioritize edge or fog computing layers for real-time decision-making, while blockchain systems can support secure post-event recordkeeping. Validation approaches must also evolve progressively, moving from simulation-based models to controlled laboratory experiments, then to pilot-scale deployments, followed by multi-season farm trials, and finally full-scale supply chain implementations. [5]

Inclusive system design is equally important, as many existing solutions exceed the technical and infrastructural capabilities of smallholder farmers. Effective deployment requires intuitive user interfaces, simplified setup processes, multilingual accessibility, and clear data governance frameworks to build trust and usability. In addition, interoperability across blockchain platforms should be treated as a fundamental design requirement rather than an optional feature, particularly for regionally connected agricultural systems and cross-border trade environments. [18]

LIMITATIONS

This review is subject to several limitations that should be considered when interpreting the findings. First, the analysis is based entirely on published peer-reviewed literature and therefore inherits any reporting biases present in the source studies. Positive results and novel architectures are more likely to appear in indexed databases than null findings or failed implementations, which may create a skewed representation of the field's actual progress. Second, the review does not include empirical data from large-scale field deployments; the majority of the reviewed systems were validated in simulation environments or small-scale pilots, and the synthesis reflects these constraints. Third, despite the structured inclusion and exclusion criteria, some degree of selection bias is unavoidable, as database coverage, search keyword specificity, and full-text accessibility may have excluded relevant studies. Fourth, the variability in reported metrics across the reviewed studies significantly limits the granularity of quantitative comparison; several key performance indicators, including throughput, latency, and energy consumption, were not consistently reported, requiring the use of NR annotations rather than direct numerical comparison. These limitations collectively underscore the need for greater methodological standardization in future IoT-blockchain agricultural research.

CONCLUSION

This review brings together research on IoT-blockchain integration in agriculture from 2022 to 2026, indicating that the reviewed studies suggest that combined systems offer advantages over standalone approaches in terms of data security, supply chain transparency, and automated transaction management. These benefits are especially visible in applications such as traceability, precision farming optimization, parametric crop insurance, and decentralized agricultural marketplaces. [1] Recent architectural trends suggest a shift toward edge-centric distributed models, which reduce dependence on centralized cloud systems and support faster, localized decision-making enabled by embedded machine learning within secure and verifiable data frameworks. Despite this progress, several challenges continue to limit large-scale adoption. Key issues include consensus latency, infrastructure costs, energy consumption, and limited technical accessibility, particularly for smallholder farmers. Addressing these challenges will require the development of energy-efficient consensus protocols, stronger edge-based intelligence, and standardized evaluation frameworks. At the same time, future systems must emphasize inclusive and user-focused design, accounting for different levels of technical capability and aligning with regional regulatory and operational requirements to ensure practical and widespread adoption. [1]

DECLARATIONS

Ethical Approval

This manuscript does not involve studies with human participants, human data, human tissue, or animals.

Competing Interests

The authors declare no competing interests related to the content of this article.

Authors' Contributions

All authors contributed equally to the conceptualization of the study, systematic literature review, architectural analysis of IoT and blockchain integration frameworks, thematic synthesis, and preparation of the manuscript.

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Availability of Data and Materials

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REFERENCES

[1] T. Miller, G. Mikiciuk, I. Durlik, M. Mikiciuk, A. Łobodzińska, and M. Śnieg, "The IoT and AI in Agriculture: The Time Is Now—A Systematic Review of Smart Sensing Technologies," Sensors, vol. 25, no. 12, p. 3583, 2025. doi: 10.3390/s25123583

[2] R. N. V. Jagan Mohan, P. S. Rayanoothala, and R. Praneetha Sree, "Smart Agriculture 5.0: Blockchain and Reinforcement Learning Synergy for Multicropping Optimization and Traceable IoT-Enabled Supply Chains," Frontiers in Blockchain, vol. 9, 2026. doi: 10.3389/fbloc.2026.1766232

[3] A. Rustemi and F. Dalipi, "Synergizing IoT, AI, and Blockchain for Smart Agriculture: Challenges, Opportunities, and Future Directions," Internet of Things, 2025. doi: 10.1016/j.iot.2025.101778

[4] F. Marzougui, M. Elleuch, and M. Kherallah, "Blockchain and IoT in Smart Agriculture: Analysis, Opportunities, Challenges, and Future Research Directions," Journal of Intelligent Agricultural Systems (JIAS), vol. 19, no. 3, pp. 104–119, 2024. doi: 10.2478/ias-2024-0008

[5] B. Mohanraj, S. Sneka, J. Udhaya Priya, S. Shyle Trana, M. Priya, and P. Sakthivel, "Next-Gen Agro-Innovation: Blockchain and IoT Convergence for Water Optimization and Weed Detection," in Proc. 9th Int. Conf. Communication and Electronics Systems (ICCES), 2024. doi: 10.1109/ICCES63552.2024.10859464

[6] M. S. M. Rafi, M. Behjati, and A. S. Rafsanjani, "Reliable and Cost-Efficient IoT Connectivity for Smart Agriculture: A Comparative Study of LPWAN, 5G, and Hybrid Connectivity Models," in Smart Computing Paradigms: Intelligence and Network Applications. Springer, Cham, 2026. doi: 10.1007/978-3-032-08240-4_33

[7] N. S. Sizan, M. A. Layek, and K. F. Hasan, "A Secured Triad of IoT, Machine Learning, and Blockchain for Crop Forecasting in Agriculture," in Innovative Computing and Communications (ICICC 2025), Springer, Singapore, 2025. doi: 10.1007/978-981-96-6883-0_13

[8] S. Padwal, S. Sattur, A. Shinde, P. Tekade, D. Salunke, and S. Rangdale, "Modernizing Agriculture with Real-Time Crop Insurance: Leveraging Blockchain, IoT, and Machine Learning," in Proc. IEEE Int. Conf. Blockchain and Distributed Systems Security (ICBDS), Pune, India, 2024. doi: 10.1109/ICBDS61829.2024.10837140

[9] M. Patel, S. Tanwar, A. Jindal, N. Alshammari, H. Pervaiz, and H. Ahmed, "A Blockchain-based Predictive Maintenance Scheme for Smart Agriculture," in Proc. IEEE/ACM 17th Int. Conf. Utility and Cloud Computing (UCC), Sharjah, UAE, 2024, pp. 405–410. doi: 10.1109/UCC63386.2024.00062

[10] S. Safeer, G. De Mastro, and C. Pulvento, "IoT-Based Climate Smart Agriculture Succeeded by Blockchain Database—A Bibliometric Analysis," Frontiers in Sustainable Food Systems, vol. 8, 2024. doi: 10.3389/fsufs.2024.1406871

[11] A. Araújo, W. Santos, and R. Oliveira, "Scalable Computational Solution for Agroclimatic Data Tracking with IoT and Multi-Blockchain Support," Computing, 2025. doi: 10.1007/s00607-025-01554-4

[12] N. M. Chacko, V. G. Narendra, M. Balachandra, and S. Rathinam, "Exploring IoT-Blockchain Integration in Agriculture: An Experimental Study," IEEE Access, vol. 11, pp. 130439–130450, 2023. doi: 10.1109/ACCESS.2023.3334726

[13] R. L. P. Urtecho, J. Rodríguez-Molina, M. Martínez-Núñez, and J. Garbajosa, "Enhancing Agriculture Through IoT and Blockchain: A VeChain-Enhanced Sustainable Development Approach for Small-Scale Agricultural Exploitations," IEEE Access, vol. 12, pp. 179962–179980, 2024. doi: 10.1109/ACCESS.2024.3506510

[14] T. Saba, A. Rehman, K. Haseeb, S. A. Bahaj, and J. Lloret, "Trust-Based Decentralized Blockchain System with Machine Learning Using Internet of Agriculture Things," CEE 2023. doi: 10.1016/j.compeleceng.2023.108674

[15] S. Tegeltija, S. Dejanović, H. Feng, S. Stankovski, G. Ostojić, D. Kučević, and J. Marjanović, "Blockchain Framework for Certification of Organic Agriculture Production," Sustainability, vol. 14, no. 19, p. 11823, 2022. doi: 10.3390/su141911823

[16] K. L. B. Krithika, Jayabalasamy G, "Survey on the Applications of Blockchain in Agriculture," Agriculture, vol. 12, no. 9, p. 1333, 2022. doi: 10.3390/agriculture12091333

[17] S. Nigam, U. Sugandh, and M. Khari, "The Integration of Blockchain and IoT Edge Devices for Smart Agriculture: Challenges and Use Cases," in Advances in Computers, Elsevier, 2022, pp. 507–537. doi: 10.1016/bs.adcom.2022.02.015

[18] A. Kaur, G. Singh, V. Kukreja, et al., "Adaptation of IoT with Blockchain in Food Supply Chain Management: An Analysis-Based Review in Development, Benefits and Potential Applications," Sensors, vol. 22, p. 8174, 2022. doi: 10.3390/s22218174

[19] P. Mishra, B. Mohanraj, G. Savithri, M. Roshini, R. Krishnamoorthy, and S. Arun, "Blockchain-Based Food Tracking for Intelligent Farming Using IoT," in Proc. Int. Conf. Inventive Computation Technologies (ICICT), 2022, pp. 522–527. doi: 10.1109/ICICT54344.2022.9850782

[20] S. A. Bhat, N.-F. Huang, I. B. Sofi, and M. Sultan, "Agriculture-Food Supply Chain Management Based on Blockchain and IoT: A Narrative on Enterprise Blockchain Interoperability," Agriculture, vol. 12, no. 1, p. 40, 2022. doi: 10.3390/agriculture12010040

[21] M. A. Ferrag, L. Shu, X. Yang, A. Derhab, and L. Maglaras, "Security and Privacy for Green IoT-Based Agriculture: Review, Blockchain Solutions, and Challenges," IEEE Access, vol. 8, pp. 32031–32053, 2020. doi: 10.1109/ACCESS.2020.2973178