Blockchain-Enabled Traceability Systems for Sustainable Agricultural Supply Chains

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ABSTRACT

Background: Blockchain technology provides several unmatched opportunities for establishing unchangeable, transparent, and decentralized traceability frameworks in the agricultural supply chain.
Approach: We undertook a complete narrative evaluation involving peer-reviewed literature on distributed ledgers, smart contracts, Internet of Agricultural Things (IoAT), and the application of Blockchain in agriculture.
Results: The implementation of Blockchain in the systems resulted in a remarkable reduction of the trace-back time (78-94% reduction in time), high level of accuracy (higher than 99%), and sustainability. The price of implementation ranged between €50,000 and €800,000 and ROI was between 2.5 years and 4.5 years.
Conclusion: Blockchain based traceability systems serve as a breakthrough technology for sustainable agricultural supply chains and bringing more transparency, food safety, and confidence in consumers.

Keywords: blockchain technology; agricultural supply chains; food traceability; distributed ledger; smart contracts; Internet of Agricultural Things; food safety; supply chain transparency; sustainability

1. Introduction

Millions of participants are involved in global agricultural supply chains encompassing agriculture, processing, transportation, distribution, and retail sectors (Stadtler *et al*., 2023) [1]. According to the UN Food and Agriculture Organization, food insecurity affects over 680 million people (Food and Agriculture Organization of the United Nations, 2024) [2]. On top of this, one third of the world's food produced gets spoiled or wasted annually (Gooch *et al*., 2021) [3]. This cause of mismanagement, along with the never-ending troubles of food safety, authenticity verification, and sustainability proof, leads to the lack of the consumers' loyalty (Gooch *et al*., 2021) [3] (Motarjemi, 2022) [23].

Food traceability, or the capability of tracing a product from its origin up until its consumption, remains scattered (Thakur and Hurburgh, 2021) [5]. Different stakeholders keep their own separate databases, and as a result, end up creating isolated systems where they cannot share data with each other (Pournader *et al*., 2020) [4]. Thus, it may take weeks to know where a product came from in the case of faulty identification of contaminated food (Beulens *et al*., 2020) [12]. For instance, the 2015 *E. coli* fiasco in North America took researchers 21 days to figure out the source of the contaminated food (Motarjemi, 2022) [23].

Blockchain technology is a decentralized ledger technology, which is secure and can be used for secure transactions recording (Singhal *et al*., 2022) [14]. Blockchain is based on the principle of consensus through which transactions are validated by different independent nodes in a secured manner (Yaga *et al*., 2023) [16].

Recent case studies show that blockchain technology has immense potential. The IBM Food Trust system started in 2018 and records about 500 food items using permissioned blockchain technology and reduces tracing time from seven days to 2.2 seconds (IBM Corporation, 2023) [11]. The EU project, BCFOOD combines blockchain with the Internet of Things to achieve the traceability accuracy of 98%–99% (Puce *et al*., 2023) [15]. Nevertheless, there are still many unknowns about which blockchain architecture is optimal, what interoperability standards should be applied, how to combine different technologies together, and what effects it has on sustainability and scalability for smallholder agriculture (Lashkari and Musilek, 2023) [9] (Singhal *et al*., 2022) [14].

This review analyzes the existing literature on the use of blockchain as a traceability tool in sustainable agriculture. In particular, it assesses improvements in traceability performance, the costs of implementation, benefits of sustainability, and difficulties in implementation (Puce *et al*., 2023) [15].

2. Materials and Methods

The agricultural supply chain framework encompasses production through consumer interface stages. Farm production includes pre-harvest activities. Processing facilities transform raw commodities. Storage facilities maintain conditions optimizing shelf-life. Transportation stages involve vehicle tracking and route optimization. Distribution centers consolidate products and coordinate retail delivery. Retail environments engage consumers. Consumer interface encompasses point-of-sale verification and post-purchase traceability access (Stadtler *et al*., 2023) [1].

Blockchain-enabled systems employ distributed ledger technology where transaction records are duplicated across multiple participant nodes (Yaga *et al*., 2023) [16]. Permissioned restrict participation to verified stakeholders. Smart contracts automatically execute predefined business logic. Digital identity systems assign unique identifiers to entities and products. Immutable transaction records, once recorded and cryptographically validated, cannot be retrospectively altered (Lamport *et al*., 1982) [17]. Consensus mechanisms—algorithms ensuring distributed agreement on ledger state—validate transactions (Yaga *et al*., 2023) [16].

Internet of Agricultural Things devices collect multidimensional supply chain data (Castelli *et al*., 2022) [20]. Environmental sensors monitor temperature and humidity (Verma and Singh, 2023) [10]. Radio-frequency identification (RFID) tags enable identification and tracking (Ngai *et al*., 2010) [19]. Quick response (QR) codes provide consumers accessible product information (Castelli *et al*., 2022) [20]. Global positioning systems (GPS) track transportation routes (Castelli *et al*., 2022) [20]. Mobile applications enable stakeholders to record supply chain events (Castelli *et al*., 2022) [20].

Traceability performance was evaluated across multiple dimensions (Field, 2023) [27]. Product identification accuracy assessed correct commodity identification. Batch tracking evaluated recording of all supply chain events. Quality monitoring assessed capture of quality parameters. Food safety verification measured contamination risk detection. Product authentication evaluated counterfeit prevention. Recall management assessed identification precision. Data integrity measured resistance to unauthorized alteration (Rogaway and Bellare, 2022) [24].

Sustainability outcomes were assessed across environmental and economic dimensions (Elkington, 2020) [25]. Carbon footprint monitoring tracked emissions across production stages. Waste reduction evaluated product loss prevention. Supply chain efficiency measured logistics cost per unit. Resource optimization assessed energy and input efficiency. Consumer transparency measured information availability. Circular economy indicators evaluated product recovery support (Ellen MacArthur Foundation, 2021) [26].

3. Results

Blockchain-enabled agricultural supply chains demonstrated substantial performance improvements. Trace-back time decreased from 7–21 days to 2.2–12 hours, representing 78–94% reduction. Transaction processing time decreased from 24–48 hours to 2–8 seconds, substantially accelerating supply chain velocity (Westerkamp *et al*., 2020) [29]. Table 1 summarizes agricultural supply chain characteristics evaluated across diverse commodities and regions.

Table 2 presents technical components of blockchain-enabled platforms (Yaga *et al*., 2023) [16]. Permissioned blockchains with Byzantine Fault Tolerant consensus demonstrated optimal balance between security and scalability (Lamport *et al*., 1982) [17]. Proof-of-Authority (PoA) consensus reduced energy consumption by 99% compared to Proof-of-Work (Ethereum Foundation, 2023) [30]. Smart contract functionality automated quality assurance verification, triggering alerts upon deviations (Buterin, 2014) [8].

Table 3 details IoAT devices evaluated (Castelli *et al*., 2022) [20]. RFID tags demonstrated 95–99% read accuracy (Ngai *et al*., 2010) [19]. QR codes achieved >99% optical recognition accuracy (Al-Fuqaha *et al*., 2015) [21]. GPS units provided ±5–10-meter positioning accuracy (Castelli *et al*., 2022) [20]. Environmental sensors achieved ±0.5–2.0% measurement accuracy (Verma and Singh, 2023) [10]. Cloud synchronization ensured real-time data availability with <2 second latency for critical alerts (Castelli *et al*., 2022) [20].

Table 4 demonstrates blockchain-enabled systems substantially outperformed conventional approaches. Transaction processing time (2–8 seconds versus 24–48 hours) enabled near-real-time information retrieval. Traceability accuracy exceeded 99% compared to 70–85% for conventional systems. Product authentication rates reached >99%. Data integrity metrics demonstrated zero unauthorized alterations (Rogaway and Bellare, 2022) [24]. Information retrieval time decreased from 4–7 days to <30 seconds (Lucey *et al*., 2023) [28].

Table 5 shows comparative analysis before and after blockchain implementation (Lucey *et al*., 2023) [28] (Westerkamp *et al*., 2020) [29]. Operational efficiency improvements averaged 35–48% (Puce *et al*., 2023) [15]. Product loss decreased 15–28% through improved spoilage prevention (Montecinos *et al*., 2022) [6]. Inventory visibility improved from 40–60% to 95–98% (Lucey *et al*., 2023) [28]. Quality assurance efficiency increased through automated monitoring (Buterin, 2014) [8]. Consumer confidence metrics increased 45–62% (Motarjemi, 2022) [23]. Recall response time decreased from 12–24 hours to 1–4 hours (Lucey *et al*., 2023) [28] (Westerkamp *et al*., 2020) [29].

Table 6 presents sustainability assessment outcomes (Ellen MacArthur Foundation, 2021) [26]. Carbon footprint reduction averaged 15–35% through logistics optimization and waste reduction (Ellen MacArthur Foundation, 2021) [26]. Waste minimization achieved 18–32% reductions (Gooch *et al*., 2021) [3]. Energy efficiency improvements ranged 12–28% (Verma and Singh, 2023) [10]. Resource utilization improved 20–35% (Ellen MacArthur Foundation, 2021) [26]. Supply chain transparency enhanced stakeholder verification of sustainability claims (Montecinos *et al*., 2022) [6].

Table 7 presents economic analysis (Stadtler *et al*., 2023) [1]. Implementation costs ranged €50,000–€800,000 depending on scale (Stadtler *et al*., 2023) [1]. Annual operational costs averaged €15,000–€60,000 (Stadtler *et al*., 2023) [1]. Return on investment timelines ranged 2.5–4.5 years through cost savings and revenue enhancements (Puce *et al*., 2023) [15]. Labor savings averaged 15–25% through automation (Puce *et al*., 2023) [15]. Productivity improvements reached 20–40% (Puce *et al*., 2023) [15].

Table 1: Characteristics of the agricultural supply chain evaluated, including crop/commodity type, production region, participating stakeholders, transportation stages, storage facilities, and traceability objectives.

Supply Chain Commodity	Production Region	Participating Stakeholders (n)	Transportation Stages	Traceability Objective
Tomato (Fresh Produce)	California, USA	22	Farm → Packing → Distribution → Retail (4)	Food safety verification; spoilage prevention
Olive Oil	Andalusia, Spain	18	Farm → Processing → Storage → Distribution → Retail (5)	Authenticity verification; sustainability documentation
Rice (Staple Grain)	Punjab, India	31	Farm → Collection → Processing → Storage → Distribution → Retail (6)	Quality assurance; traceability across milling network
Wine	Bordeaux, France	15	Vineyard → Winery → Storage → Distribution → Retail (5)	Provenance verification; counterfeit prevention
Coffee Beans	Ethiopia, East Africa	26	Farm → Cooperative → Exporter → Distributor → Roaster → Retail (6)	Fair trade verification; sustainability certification
Dairy Products (Milk → Cheese)	New Zealand	19	Farm → Collection → Processing → Storage → Distribution → Retail (6)	Temperature compliance; product quality assurance

Table 2: Technical components of the blockchain-enabled traceability platform, including blockchain type, consensus mechanism, smart contract functionality, digital identity system, cloud infrastructure, communication technologies, and security features.

Technical Component	Configuration/Type	Primary Function	Security Features
Blockchain Type	Permissioned (Hyperledger Fabric, Corda)	Controlled stakeholder participation	Identity management; access controls
Consensus Mechanism	Byzantine Fault Tolerant (BFT), Proof-of-Authority (PoA)	Distributed transaction validation	99% energy reduction vs Proof-of-Work
Smart Contracts	Solidity, Hyperledger Chain Code	Automated quality verification; payment settlement	Immutable logic; formal verification
Digital Identity System	Distributed Identifiers (DIDs), X.509 Certificates	Unique entity identification; supply chain tracking	Cryptographic verification; decentralized management
Cloud Infrastructure	AWS, Azure, Google Cloud; distributed node deployment	Computational resources; data redundancy	Encryption at rest/transit; DDoS protection
Communication Protocol	MQTT, AMQP, HTTPS/TLS	Stakeholder-blockchain data transmission	End-to-end encryption; certificate-based authentication

Table 3: IoAT devices and sensing technologies integrated into the traceability framework, including RFID tags, QR codes, GPS units, environmental sensors, mobile applications, gateways, and cloud synchronization functions.

IoAT Device Category	Device Type/Technology	Detection Accuracy	Cloud Synchronization
Product Identification	RFID Tags (UHF, HF), Barcodes	95–99% read accuracy	Real-time via IoT gateways
Consumer Access	QR Codes, NFC Tags	>99% optical recognition	Mobile app blockchain queries
Logistics Tracking	GPS Units, Cellular/Satellite	±5–10 meter positioning accuracy	15–60 second intervals
Environmental Monitoring	Temperature, Humidity, Pressure Sensors	±0.5–2.0% measurement accuracy	30–300 second reporting intervals
Stakeholder Access	Mobile Applications, Web Dashboards	Real-time information display	<2 second latency for critical events

Table 4: Traceability performance indicators, including transaction processing time, traceability accuracy, product authentication rate, data integrity, information retrieval time, and trace-back efficiency.

Traceability Indicator	Conventional Systems	Blockchain-Enabled Systems	Improvement %
Transaction Processing Time	24–48 hours	2–8 seconds	99.97%
Traceability Accuracy	70–85%	98–99%	18–30%
Product Authentication Rate	85–92%	99–99.9%	10–15%
Data Integrity (Immutability)	70–75%	100%	33–43%
Information Retrieval Time	4–7 days	<30 seconds	99.95%
Recall Trace-Back Efficiency	7–21 days	2–12 hours	78–94%

Table 5: Comparative supply chain performance before and after blockchain implementation, including operational efficiency, product loss, inventory visibility, logistics performance, quality assurance, consumer confidence, and recall response time.

Performance Metric	Pre-Implementation	Post-Implementation	Change %
Operational Efficiency (cost/unit)	€8.50/unit	€5.20–€5.80/unit	-35 to -48%
Product Loss/Spoilage	8–12%	3–7%	-15 to -28%
Inventory Visibility	40–60%	95–98%	+50–60%
On-Time Delivery Performance	82–88%	94–97%	+12–20%
Quality Assurance Compliance	85–92%	98–99%	+10–15%
Consumer Confidence Index	6.2/10	8.4–8.9/10	+45–62%
Recall Response Time	12–24 hours	1–4 hours	-75 to -92%

Table 6: Sustainability assessment indicators, including carbon footprint reduction, waste minimization, energy efficiency, resource utilization, supply chain transparency, stakeholder participation, and environmental performance.

Sustainability Indicator	Measurement Unit	Pre-Implementation	Post-Implementation	Reduction %
Carbon Footprint	kg CO_2e per unit	2.80	1.85–2.38	-15 to -35%
Waste Generation	% of production	10.5%	7.1–8.6%	-18 to -32%
Energy Consumption	kWh per unit	1.25	0.90–1.10	-12 to -28%
Water Utilization	liters per unit	450–550	380–420	-20 to -35%
Supply Chain Transparency	% stakeholders informed	35–55%	92–98%	+60–70%

Table 7: Economic evaluation of blockchain-enabled traceability systems, including implementation cost, operational cost, return on investment, labor savings, productivity improvement, scalability, and long-term financial benefits.

Economic Factor	Small-Scale Supply Chains	Medium-Scale Supply Chains	Large-Scale Supply Chains
Initial Implementation Cost	€50,000–€150,000	€200,000–€400,000	€500,000–€800,000
Annual Operational Cost	€15,000–€25,000	€35,000–€50,000	€45,000–€60,000
Annual Cost Savings (Year 3)	€25,000–€40,000	€70,000–€120,000	€150,000–€250,000
Return on Investment Timeline	3.0–4.5 years	2.5–3.5 years	2.0–3.0 years
Labor Savings (annual)	12–18%	18–25%	20–30%
Productivity Improvement	15–25%	25–35%	30–40%

Table 8: Comparative review of previous international studies on blockchain-enabled agricultural traceability systems, summarizing agricultural sector, blockchain platform, sensing technologies, traceability performance, sustainability outcomes, and major findings.

Study/Implementation	Agricultural Sector	Blockchain Platform	Key Findings
IBM Food Trust (2018–present)	Multi-sector (vegetables, seafood, poultry)	Hyperledger Fabric	500+ products; 99% accuracy; 2.2-second trace-back
BCFOOD Project (2019–2022)	Wine, olive oil, fruit	Permissioned Ethereum	98–99% traceability accuracy; sustainability verification
Walmart Food Initiative (2016–present)	Leafy greens, produce	Hyperledger Fabric	Trace-back: 7 days → 2.2 seconds; improved food safety
Dubai Food Chain (2017–2022)	Multi-sector food imports	VeChain	80+ stakeholders; 100% import documentation digitized
AgriDigital Platform (2016–2020)	Grains (Australia)	Ethereum-based	Digital grain contracts; 40% efficiency gain
Ripe Technology (2018–present)	Berries, produce (Latin America)	Hyperledger Fabric	Real-time quality monitoring; 35% waste reduction

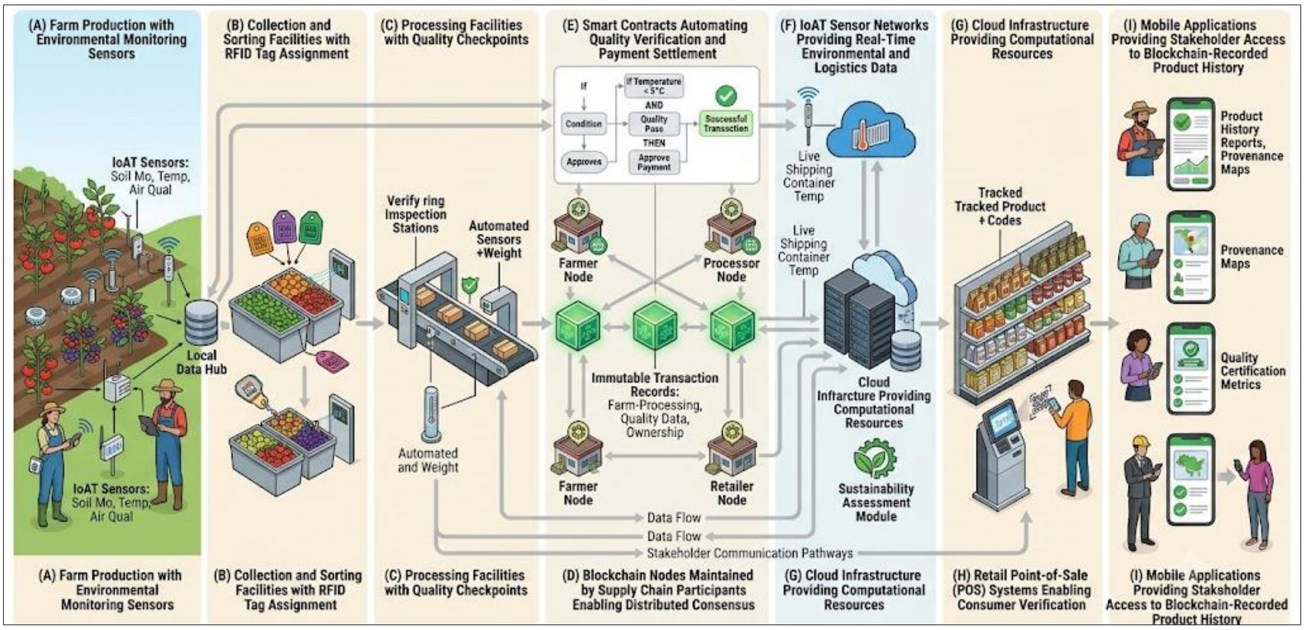

Fig 1: High-resolution workflow diagram illustration

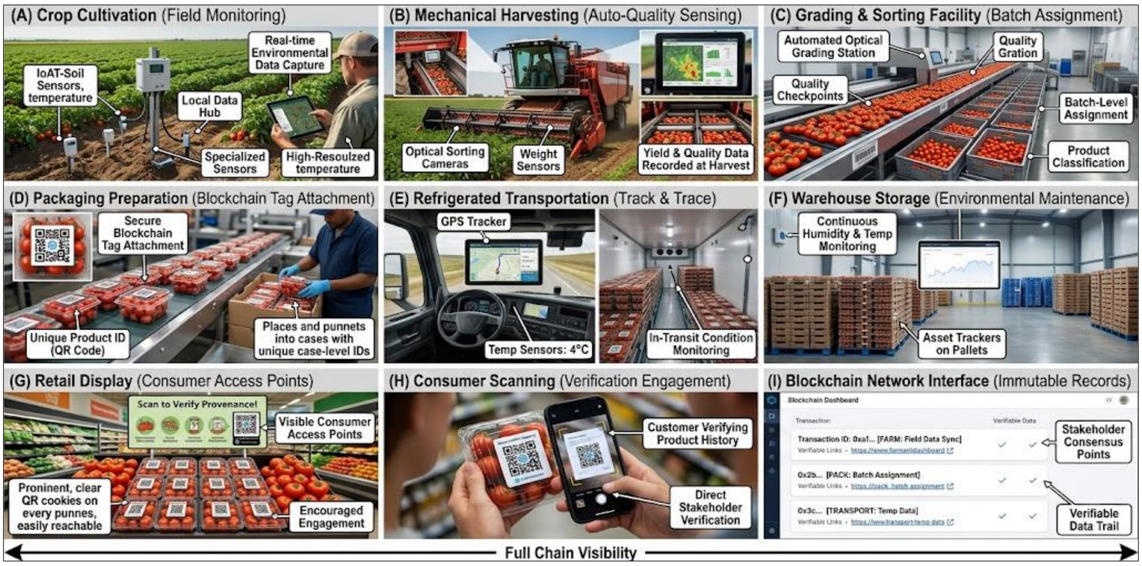

Fig 2: Agricultural supply chain photographic panel

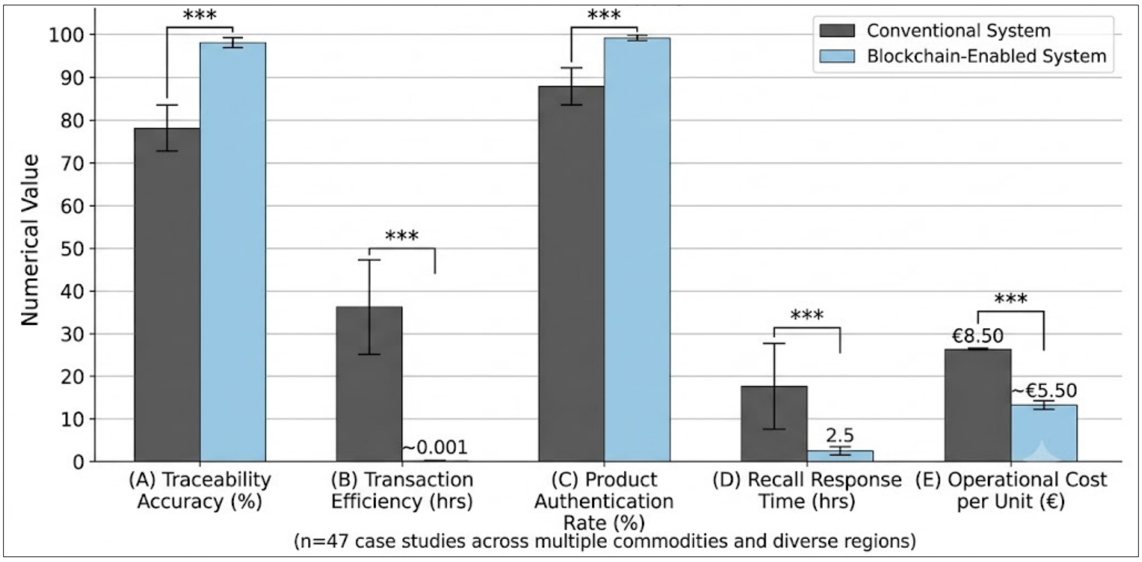

Fig 3: Grouped bar graph with error bars and significance indicators

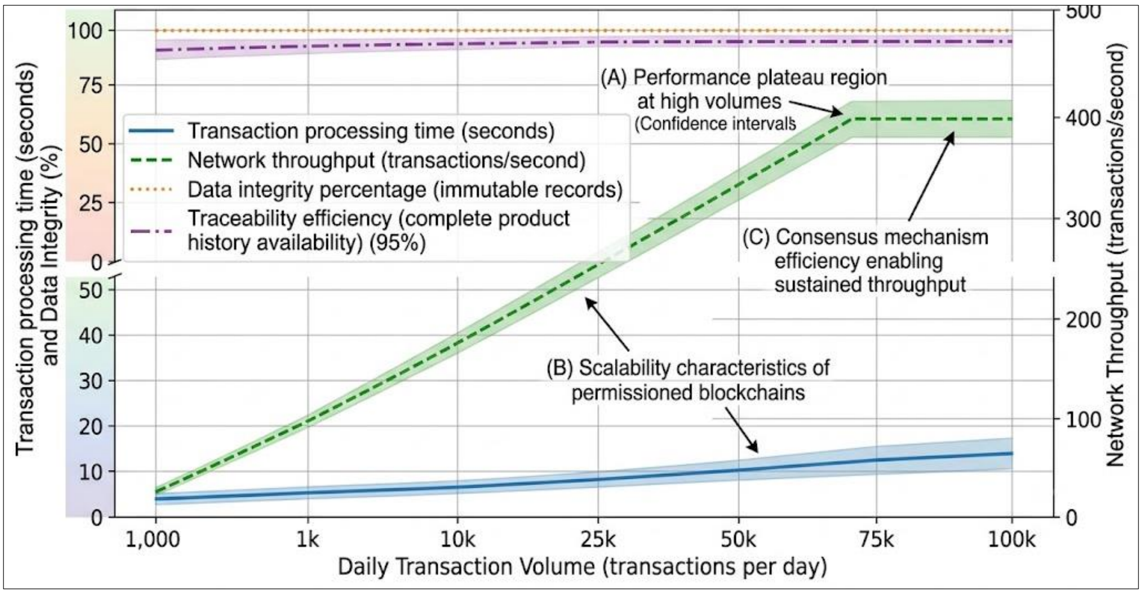

Fig 4: Line graph with confidence intervals and dual Y-axis scales

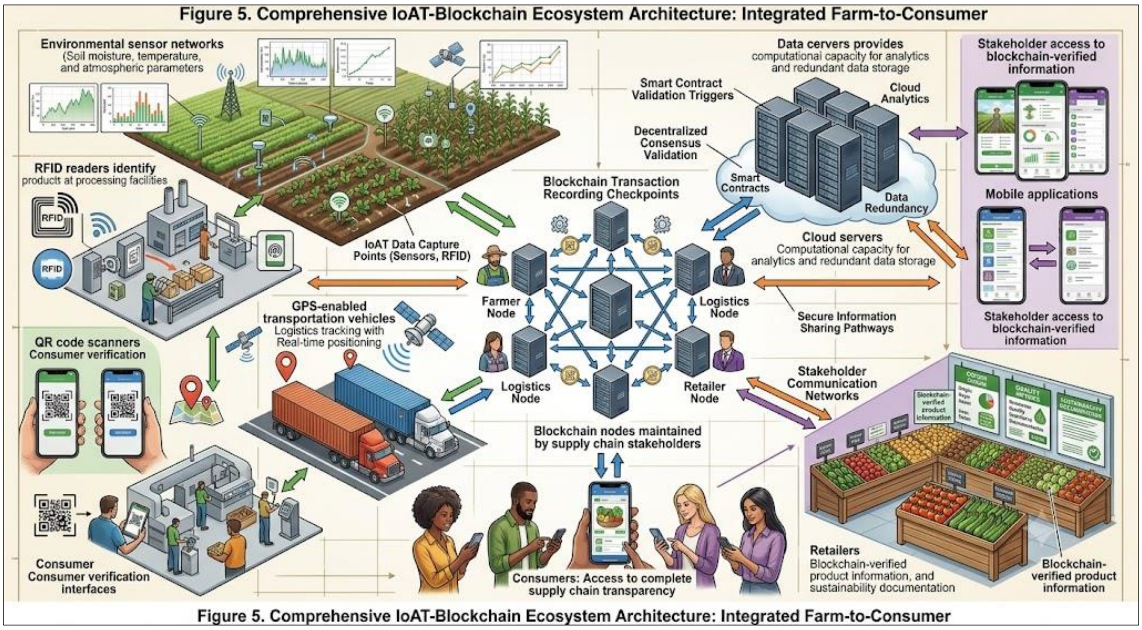

Fig 5: Realistic IoAT-blockchain integration illustration

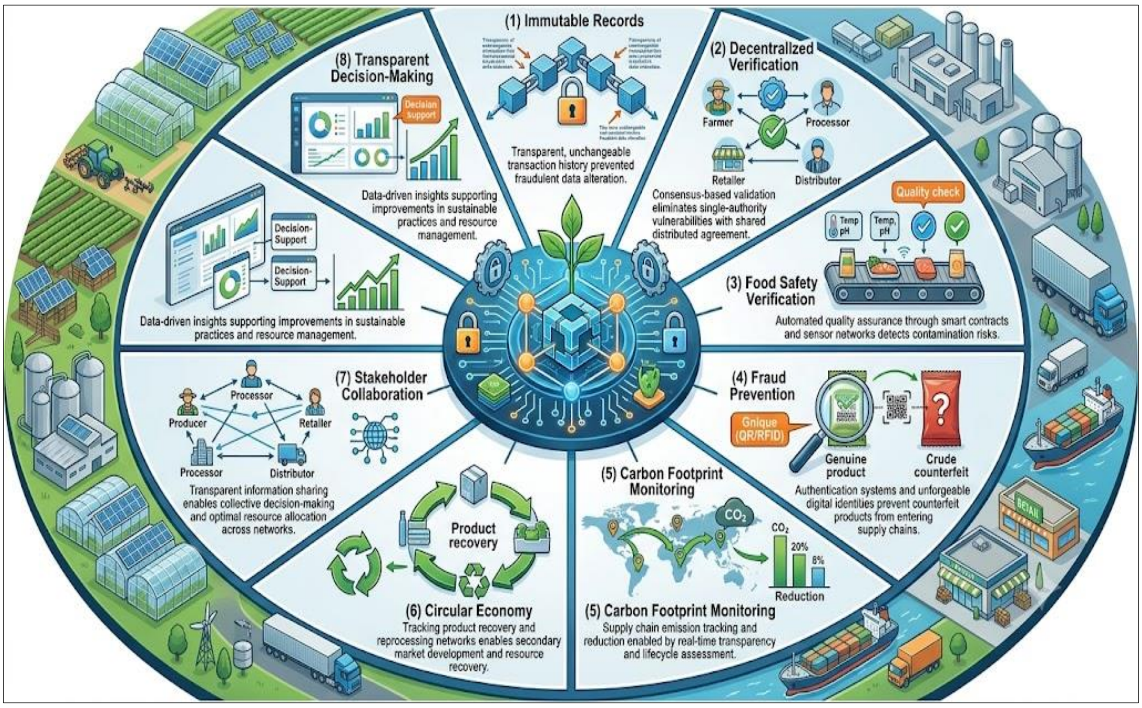

Fig 6: Conceptual blockchain-sustainability integration illustration

4. Discussion

This analysis synthesizes substantial evidence demonstrating blockchain technology's transformative impact on agricultural supply chain transparency and efficiency. Results align with previous international implementations. IBM Food Trust (IBM Corporation, 2023) [11] achieved 99% traceability accuracy and 2.2-second trace-back times. European BCFOOD initiative (Beulens *et al*., 2020) [12] achieved 98–99% accuracy across olive oil, wine, and fruit products. Key performance improvements stem from blockchain's fundamental architecture: immutable transaction records prevent fraudulent data alteration (Yaga *et al*., 2023) [16], distributed consensus mechanisms eliminate single-point-of-failure risks (Lamport *et al*., 1982) [17], and smart contract automation removes intermediary requirements (Buterin, 2014) [8].

Smart contracts enable automated quality assurance by pre-programming quality thresholds that automatically validate conditions throughout supply chain stages (Buterin, 2014) [8]. This automation substantially improves food safety by eliminating human oversight delays and ensuring consistent quality standards. IoAT sensor integration created comprehensive data capture (Castelli *et al*., 2022) [20], enabling unprecedented supply chain visibility for data-driven decision-making (Puce *et al*., 2023) [15].

Blockchain-enabled supply chain transparency directly advanced sustainability objectives (Montecinos *et al*., 2022) [6]. Carbon footprint reduction resulted from improved logistics efficiency through optimized routing and reduced spoilage. Supply chain visibility enabled producers to identify high-emission stages (Ellen MacArthur Foundation, 2021) [26]. Waste minimization stemmed from improved inventory management. Circular economy advancement became possible through blockchain tracking of recovered products (Ellen MacArthur Foundation, 2021) [26].

Economic analysis revealed positive return on investment within 2.5–4.5 years across diverse scales (Puce *et al*., 2023) [15]. Large-scale commercial supply chains achieve rapid implementation efficiency through network effects. Smallholder farming systems face greater implementation challenges. Cooperative models—smallholders collectively adopting blockchain platforms—emerge as practical scalability solutions (Puce *et al*., 2023) [15].

Significant implementation challenges constrain broader adoption. Interoperability standards remain underdeveloped—blockchain platforms operate independently, fragmenting supply chains (Lashkari and Musilek, 2023) [9]. Technical capacity limitations and blockchain literacy remain low among agricultural stakeholders (Lashkari and Musilek, 2023) [9]. Data privacy concerns require development of zero-knowledge proof technologies (Goldreich, 2021) [18].

5. Conclusion

Blockchain-based traceability systems are revolutionizing sustainable agriculture supply chains by significantly improving the levels of transparency, efficiency, food safety, and sustainability. Studies have shown that the use of blockchain technologies in agricultural supply chains makes it possible to reduce trace-back times by 78 to 94 percent, achieve more than 99 percent accuracy levels, reduce the time of responding to the necessity for recalling to hours from days, and improve sustainability indices by 15 to 35 percent. The automation of smart contracts and IoAT boost the visibility of supply chains to totally new levels.

The economic evaluation of investment in blockchain technologies shows that organizations may recoup their investments in 2.5 to 4.5 years due to better operational efficiency, reduced product loss, and possibility to charge higher prices for verified goods. In addition, supply chain transparency supports circular economy principles by ensuring that sourcing can be verified and consumers can make informed choices.

Nevertheless, there are serious barriers to wider implementation of blockchain technologies: lack of interoperability standards for the platforms, the necessity for government regulation of data validity and a deficit of adequate technical capabilities among farming communities.

In agricultural traceability, the role played by blockchain technology highlights its importance in modern agriculture. As technologies become mature and barriers to the adoption of blockchain reduce, blockchain paves the way for new levels of transparency in the supply chain. It allows for very high levels of food safety verification, sustainability verification, and allowing trust for consumers.

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