

Blockchain-Based Supply Chain Transparency for Agricultural Produce: A Comprehensive Review of Distributed Ledger Architectures, Smart Contracts, QR-Code Traceability, and IoT Integration

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Abstract- Agricultural produce passes through the farmer, processor, distributor, retailer and consumer before it is eaten, and fragmented, manual or centrally held records make it difficult to verify the origin, quality and movement of a product. Blockchain, a distributed ledger that keeps time-stamped, tamper-resistant records, has therefore been widely proposed to improve transparency and traceability in agri-food supply chains. This paper presents a focused narrative review of verified peer-reviewed studies on blockchain-based traceability of agricultural produce. It examines four connected themes: blockchain and distributed ledger foundations; smart contracts for automated, batch-level recording of supply-chain events; consumer-facing verification through QR codes; and integration with Internet of Things (IoT) and radio-frequency identification (RFID) sensing for data capture. The literature shows that blockchain, smart contracts and IoT can be combined into working farm-to-consumer prototypes, and that review articles consistently point to benefits for traceability, trust and food safety. However, most studies are prototypes or conceptual frameworks, and the reviewed work offers limited evidence on large-scale deployment, scalability, cost, farmer adoption, regulatory fit and, above all, the trustworthiness of data entered at the source, since a ledger can preserve but not verify what is written to it. The review contributes a comparative analysis of representative studies, a proposed conceptual architecture linking batch-level ledger records, smart contracts, QR-code access and IoT sensing, and a prioritised agenda of research gaps and future directions.

Keywords— Blockchain, Agricultural Supply Chain, Traceability, Smart Contracts, QR Code, Internet of Things, Distributed Ledger

I. INTRODUCTION

Agricultural produce reaches the consumer through a chain of stages: the farmer, the processor, the distributor, the retailer and finally the consumer. Each stage creates information about the product, such as its origin, handling, storage conditions, quality checks and ownership, but this information is usually held in separate paper or centralised digital records. Where records are fragmented, manual or controlled by a single party, the origin, quality and movement of a product are hard to verify, and the records are exposed to error and unauthorised change [1], [2].

Blockchain was introduced by Nakamoto [3] as a peer-to-peer ledger in which transactions are grouped into time-stamped blocks linked by

cryptographic hashes, so that a recorded entry cannot be altered without detection. Later work extended the idea from digital currency to other domains, and systematic reviews list supply chains among the main application areas [4]. In agriculture and food, reviews report growing interest in using blockchain to improve transparency, traceability and trust between stakeholders [1], [2], [5].

Three developments make blockchain relevant to agricultural traceability: smart contracts that automate and enforce the recording of supply-chain events at batch level [6]; machine-readable identifiers such as QR codes that let consumers query the recorded history; and IoT and RFID devices that capture data automatically [7]–[9]. This paper reviews these strands together, asks how mature the evidence is, and proposes a conceptual architecture. Its contributions are: (i) a structured narrative review

of verified studies; (ii) a comparative analysis of representative work; (iii) identification of research gaps; and (iv) a conceptual farm-to-consumer architecture with a research agenda. Section II describes the methodology, Section III reviews the literature, Section IV compares the studies, Section V discusses challenges and gaps, Section VI proposes research directions and Section VII concludes.

II. REVIEW METHODOLOGY AND LITERATURE SELECTION CRITERIA

1. Search Strategy

Candidate studies on blockchain-based agri-food traceability were selected using combinations of the terms blockchain, distributed ledger, agricultural supply chain, agri-food, traceability, smart contract, QR code, IoT and RFID, giving priority to widely cited peer-reviewed journal and conference papers and to review articles. Each candidate was then checked against its publisher or DOI metadata record.

2. Inclusion and Exclusion Criteria

A source was included when it (i) was peer reviewed, (ii) addressed blockchain or distributed ledger technology for agri-food traceability or transparency, or one of its enabling technologies (smart contracts, IoT or RFID capture, product identifiers), (iii) stated a method, system or review contribution, and (iv) had a verifiable DOI record. Marketing material, blog posts, vendor white papers and entries that could not be verified were excluded. The original Bitcoin paper [3] was retained as the foundational reference.

3. Screening Outcome and Limitations

Eleven sources were retained: one foundational paper [3], five review or perspective articles [1], [2], [4], [5], [10] and five primary studies describing systems or case studies [6]–[9], [11]. The review is narrative rather than systematic: logged queries of Scopus or Web of Science were not performed, study counts are not reported, and the verified set concentrates on 2016–2020 publications. Later studies are not covered and are a natural extension.

III. LITERATURE REVIEW

1. Blockchain and Distributed Ledger Foundations

A blockchain is a ledger replicated across many nodes. Transactions are collected into blocks; each block stores a timestamp and the hash of the previous block, so changing an old record would change every later hash and be rejected by the network [3]. Agreement on the next block is reached through a consensus mechanism, which removes the need for a central record keeper. Platforms are commonly classified as public, where anyone may join, and permissioned, where participants are known and admitted [4]. For agricultural supply chains a permissioned design is a natural fit, because the stakeholders are identifiable farmers and organisations.

2. Agricultural Supply Chains and Traceability Needs

Agri-food chains are long, multi-party and heterogeneous, with perishable and seasonal products and actors ranging from smallholders to retailers [1], [5]. Traceability, the ability to follow a product forward and backward through the chain, supports food-safety recalls, origin and organic claims, and consumer trust [2]. Surveys of the area find that blockchain is mainly proposed to give all parties a shared, tamper-evident view of these events instead of separate records [1], [2], [5]. A food-distribution case study, framed around the question of whether stakeholders know where their food has been, illustrates the consumer-side motivation [11].

3. Smart Contracts and Batch-Level Tracking

Smart contracts are programs stored on the ledger that execute automatically when their conditions are met. In traceability they can create a batch record, transfer custody from one actor to the next and reject updates from unauthorised parties. Salah et al. [6] built a soybean traceability system using Ethereum smart contracts and discussed its cost and security, showing that a chain from farmer to buyer can be coordinated without a trusted central party. Batch-level identification, in which each lot of produce receives a unique identifier that follows it

through processing and distribution, is a practical unit of tracking because recording every individual item on-chain is rarely economical.

4. IoT and RFID Integration

Manual data entry is slow and open to error, so several studies connect sensing devices to the ledger. Tian [7] proposed an agri-food traceability system for China that combines RFID identification with blockchain. Caro et al. [8] reported a practical implementation of blockchain-based traceability in agri-food supply chain management in which IoT devices supply the data. Tsang et al. [9] presented a blockchain-driven IoT architecture for food traceability with an integrated consensus mechanism.

5. QR Code-Based Consumer Verification

A QR code printed on the package or label lets a consumer open the recorded history of a product with a smartphone and no special equipment. The code carries a batch identifier or a link; the verification service reads it, queries the ledger and displays the recorded stages. Because the ledger stores the history and the QR code only points to it,

a copied or reprinted code could still point to a genuine record, so unique, non-guessable identifiers and tamper-evident labels are design concerns rather than solved problems.

6. Data Trust and the Limits of the Ledger

Pearson et al. [10] argue that distributed ledgers are not a panacea for food traceability. A ledger keeps a record unchanged once it is written, but it cannot by itself show that the information entered at the source was true. Sensor failure, mislabelling or dishonest entry produce a permanent but wrong record, so data capture, the identity of the data provider and independent verification matter as much as the ledger itself.

IV. COMPARATIVE ANALYSIS OF EXISTING STUDIES

Table I summarises representative primary studies and review articles. Because the studies differ in scope, platform and evaluation, they are compared qualitatively rather than numerically.

Table 1: Comparison of Representative Studies on Blockchain-Based Agri-Food Traceability

Author, year	Type / objective	Technologies	Main contribution	Scope limitation
Tian, 2016 [7]	System proposal; China agri-food chain	RFID, blockchain	Combines RFID identification with blockchain for chain-wide traceability	Early design-stage proposal
Caro et al., 2018 [8]	Implementation; agri-food traceability	Blockchain, IoT	Practical implementation feeding IoT data into blockchain traceability	Small-scale implementation
Salah et al., 2019 [6]	Implementation; soybean chain	Ethereum smart contracts	Smart-contract traceability from farmer to buyer with cost and security discussion	Single commodity
Tsang et al., 2019 [9]	Architecture; food traceability	Blockchain, IoT, consensus design	IoT-driven traceability with an integrated consensus mechanism	Single sector focus
Bumblauskas et al., 2020 [11]	Case study; food distribution	Blockchain	Use case on knowing where food has been in the distribution chain	Single case study
Kamilaris et al., 2019 [1]	Review; agriculture and food chains	Blockchain (survey)	Surveys the rise of blockchain in agriculture and food supply chains	Review; no new system

Antonucci et al., 2019 [5]	Review; agri-food sector	Blockchain (survey)	Reviews blockchain applications in the agri-food sector	Review; no new system
Feng et al., 2020 [2]	Review; agri-food traceability	Blockchain (survey)	Reviews development methods, benefits and challenges of blockchain traceability	Review; no new system
Casino et al., 2019 [4]	Systematic review; all sectors	Blockchain (survey)	Classifies blockchain applications and open issues across domains	Not agriculture-specific
Pearson et al., 2019 [10]	Perspective; food traceability	Distributed ledgers	Argues ledgers alone do not guarantee trustworthy traceability	No implementation

Three patterns emerge. First, the primary studies are system proposals, prototype implementations or case studies rather than long-term field deployments [6]–[9], [11]. Second, the review articles repeatedly describe the field as promising but still immature [1], [2], [5]. Third, the perspective in [10] shows that the quality of source data limits what any ledger can guarantee. Since platforms, products and evaluation methods differ, no single technology stack can be declared best on the verified evidence.

V. RESEARCH CHALLENGES AND IDENTIFIED GAPS

The following gaps are drawn from the reviewed literature and from reasoning about the system design.

- (i) Trust in source data. A ledger preserves what is written but cannot verify it, so incorrect or dishonest entries remain permanently recorded [10].
- (ii) Scalability, throughput and cost. Consensus design and transaction cost affect whether a platform can handle large volumes of batch events [6], [9], and reviews list scalability among the open issues [1], [2].
- (iii) Limited field evidence.

The primary studies are prototypes or case studies [6]–[9], [11], so performance across seasons, regions and many stakeholders is not established. (iv) Adoption by farmers. Smallholders may lack devices, connectivity and digital skills, a barrier noted in reviews of the sector [1], [5]. (v) Interoperability and

standards. Separate platforms may use different data models, so records cannot easily be shared across chains [4]. (vi) Privacy of commercial data. Prices and supplier relationships may be sensitive, so what is stored on-chain and what is kept off-chain must be chosen carefully. (vii) Regulation and governance. Reviews identify regulatory and organisational questions as open [1], [2]. (viii) Consumer-side usability. Little of the reviewed work evaluates whether consumers scan QR codes and understand the history they see.

VI. PROPOSED RESEARCH DIRECTIONS

1. Proposed Conceptual Architecture

Fig. 1 presents a conceptual architecture derived from the reviewed systems. Supply-chain actors (layer 1) produce events about each batch. Data are captured by IoT sensors, RFID readers, GPS devices or manual entry, and each record is digitally signed by its provider (layer 2).

Smart contracts create batches, transfer custody and enforce access rules (layer 3) [6]. Batch events are written to a permissioned blockchain, with large documents stored off-chain and only their hashes kept on the ledger (layer 4) [3].

A QR-code service resolves the batch identifier printed on the label into the recorded history (layer 5), which the consumer views on a smartphone (layer 6).

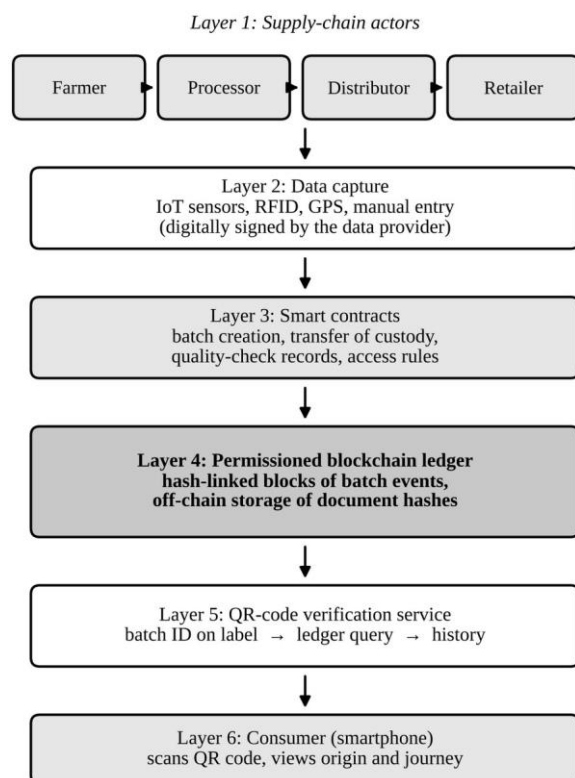


Fig.1. Proposed conceptual architecture for blockchain-based agricultural supply chain transparency (conceptual, not experimentally validated)

2. Working Principle

The proposed working principle has five steps. (1) The farmer registers a harvest as a new batch, and the smart contract assigns a unique batch identifier. (2) Each later actor records receipt, processing, storage and dispatch events against that identifier, using sensor readings where available. (3) The network validates each signed transaction by consensus and appends it to the ledger. (4) A QR code carrying the batch identifier is attached to the retail package. (5) The consumer scans the code and the service returns the ledger history, from farm to shelf.

3. Directions Requiring Investigation

Priorities include (i) pilot trials of batch-level tracking with real farmers and processors across seasons; (ii) trusted data capture, combining tamper-resistant sensors, signed records and independent audits to reduce the source-data problem [10]; (iii) cold-chain monitoring and GPS tracking through IoT sensors [9];

(iv) AI-based quality verification to check entries and flag anomalies; (v) more advanced smart contracts for automated payments and compliance checks [6]; (vi) shared data models for interoperability between platforms [4]; (vii) cost-benefit and adoption studies for smallholders [1], [5]; and (viii) usability studies of QR-code verification with consumers.

VII. CONCLUSION AND FUTURE SCOPE

Agricultural supply chains need better transparency and traceability, and blockchain can provide a secure, tamper-resistant record of product movement from the farmer to the consumer. The reviewed literature shows that smart contracts, RFID and IoT capture and consumer-facing identifiers can be combined into working prototypes, and that review articles expect gains in trust, food safety and traceability. The evidence base is, however, dominated by prototypes and conceptual frameworks, and the trustworthiness of source data, scalability, cost, adoption and governance remain open problems.

Future work should extend this review to the most recent studies, test the proposed architecture in a pilot with a real agricultural chain, and add IoT sensors, GPS tracking, AI-based quality verification and more advanced smart contracts, evaluating each against cost, usability and the reliability of the data it records.

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