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Blockchain-Based Supply Chain Transparency for Agricultural Produce

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Abstract

Food safety and economic growth depend on agricultural supply chains, yet these systems frequently struggle with fraud, inefficiency, and a lack of transparency. Because traditional centralized systems struggle with traceability and stakeholder trust, it is challenging to ensure the quality and authenticity of produce. Although modern technologies like cloud platforms and the Internet of Things (IoT) offer partial solutions, they remain susceptible to data manipulation and interoperability issues. Blockchain offers a potential alternative for improving efficiency, accountability, and trust due to its decentralized and tamper-resistant nature. Creating a blockchain-based framework to improve transparency in agricultural product supply chains is the main goal of this project. This framework enables real-time tracking of products from farm to consumer, ensuring data integrity at every stage. It enhances coordination among farmers, distributors, retailers, and regulators through secure and transparent information sharing. Ultimately, the proposed system aims to reduce fraud, minimize losses, and strengthen consumer confidence in agricultural products.

Keywords: *Blockchain Technology, Supply Chain Transparency, Agricultural Produce, Traceability.*
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I. INTRODUCTION

Agricultural supply chains play a critical role in ensuring the delivery of safe, high-quality products from producers to consumers. However, these systems are often characterized by limited transparency, inefficiencies, and vulnerability to fraud, which can negatively affect both farmers' incomes and consumer trust. Conventional supply chain systems typically rely on centralized data management, making it difficult to ensure traceability, accountability, and fair value distribution across stakeholders. As a result, issues such as price manipulation, information asymmetry, and lack of product authenticity remain persistent challenges in the agricultural sector.

To address these limitations, various digital technologies have been introduced, including cloud-based platforms, Internet of Things (IoT) systems, and mobile applications. These technologies enable real-time data collection and monitoring of agricultural processes, improving operational efficiency and decision-making (Kamilaris et al., 2019; Feng et al., 2020). Government-supported platforms such as Agmarknet and eNAM also provide market price information to farmers, aiming to reduce dependency on intermediaries. However, these solutions often face challenges related to data reliability, interoperability, and accessibility, particularly in rural

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environments with limited digital literacy and infrastructure. In addition, centralized systems remain susceptible to data manipulation, which can undermine stakeholder trust (Zhao et al., 2019; Abeywardena et al., 2021).

Blockchain technology has emerged as a promising solution to enhance transparency and trust in supply chain management. Its decentralized and immutable nature allows transactions to be securely recorded and verified without reliance on a central authority (Kamilaris et al., 2019; Zhao et al., 2019). Previous studies have demonstrated the potential of blockchain to improve traceability, reduce fraud, and enhance accountability in food supply chains (Kamble et al., 2020; Nayyar et al., 2021). Furthermore, the integration of blockchain with IoT and QR code mechanisms enables end-to-end visibility, allowing stakeholders to track product origin, handling conditions, and pricing history throughout the supply chain (Dey & Saha, 2021; Khan & Salah, 2018). Despite these advancements, many existing solutions lack user-centric design, scalability, and effective integration with real-time market data, particularly for small-scale farmers and rural ecosystems.

In addition to technological limitations, socio-economic challenges remain significant. Farmers in many regions continue to face restricted access to accurate and timely market information, often relying on intermediaries who may influence pricing for their own benefit. This imbalance reduces farmers' bargaining power and leads to unstable income conditions. At the same time, consumers have limited visibility into the origin and quality of agricultural products, which affects their trust. These issues highlight the need for an integrated system that not only ensures transparency but also supports fair and inclusive participation across all stakeholders.

In light of these challenges, this study proposes a blockchain-based framework to enhance transparency in agricultural supply chains. The framework integrates blockchain technology, QR code mechanisms, and IoT-based monitoring to enable secure, real-time tracking of agricultural produce from farm to consumer. By linking physical products with immutable digital records, the system aims to improve traceability, strengthen stakeholder trust, and support fair value distribution. The proposed approach is expected to provide a practical and scalable solution for building a transparent and sustainable agricultural supply chain ecosystem.

II. LITERATURE REVIEW

A. Digital Technologies in Supply Chains for Agriculture

The integration of digital technologies has significantly transformed agricultural supply chains, enabling more efficient production, distribution, and consumption processes. Technologies such as mobile applications, Internet of Things (IoT) sensors, GPS tracking, and cloud-based platforms allow real-time monitoring of crop conditions, logistics, and market dynamics, thereby improving operational visibility and decision-making (Kamilaris et al., 2019; Feng et al., 2020). In addition, government-supported platforms such as Agmarknet and eNAM have contributed to the digitalization of agricultural markets by providing access to mandi-level pricing data and facilitating electronic trading mechanisms. These initiatives aim to reduce information asymmetry and improve farmers' access to market intelligence.

Despite these advancements, several limitations persist, particularly in rural contexts. Issues related to low digital literacy, language barriers, and limited internet connectivity often restrict effective adoption of these systems (Abeywardena et al., 2021). Furthermore, many existing digital platforms rely on centralized architectures, making them vulnerable to data manipulation and reducing trust among stakeholders (Zhao et al., 2019). To address these challenges, integrating digital tools into user-friendly mobile interfaces has been proposed to improve accessibility and inclusivity in agricultural ecosystems. Additionally, complementary technologies such as digital payment systems and QR code tagging have been introduced to streamline transactions, enhance traceability, and reduce reliance on intermediaries (Khan & Salah, 2018; Dey & Saha, 2021). These developments collectively contribute to building a more transparent and data-driven supply chain environment. The roles of key stakeholders in such a system are summarized in Table 1.

Table 1. Stakeholders in Blockchain-Based Agriculture Supply Chain

Stakeholders	Role
Farmer	Enters production and harvest data
Processor	Updates quality and packaging details
Transporter	Provides transit and condition tracking
Distributor	Manages inventory and dispatch
Retailer	Shares product availability and pricing
Consumer	Verifies authenticity via QR code

B. Research Gaps and Blockchain Applications

Blockchain technology has emerged as a promising solution for addressing transparency and trust issues in agricultural supply chains due to its decentralized, secure, and immutable data structure (Zhao et al., 2019; Kamilaris et al., 2019). It enables reliable tracking of assets and transactions across multiple stakeholders without requiring a central authority. Applications of blockchain in agriculture include product traceability, crop certification, and the use of smart contracts for automating payments and insurance processes (Kamble et al., 2020; Nayyar et al., 2021). Several studies have demonstrated that blockchain can enhance food safety, reduce fraud, and improve accountability within supply chain operations (Feng et al., 2020; Rejeb et al., 2020).

However, despite these promising developments, important research gaps remain. Many existing blockchain-based solutions lack scalability and user-centric design, particularly for smallholder farmers and low-literacy populations (Abeywardena et al., 2021). In addition, the integration of blockchain systems with real-time market data from public platforms such as Agmarknet and eNAM has not been extensively explored. Prior studies also indicate that interoperability between blockchain platforms and existing agricultural information systems remains a challenge (Behnke & Janssen, 2020). Furthermore, the broader socioeconomic impacts of blockchain adoption, such as its effects on farmers' incomes, consumer trust, and policy alignment, have not been sufficiently investigated (Nikolaou, 2022). Addressing these gaps is essential to ensure that blockchain-based agricultural solutions are not only technically robust but also inclusive, scalable, and sustainable in real-world contexts.

III. RESEARCH METHOD

A. Data Collection Techniques

The study's data collection strategy aimed to capture the social and technical aspects of agricultural transparency. Using a multilingual mobile application, farmers registered crop details, including crop type, quantity, harvest date, and location. Real-time access to mandi-level crop prices was ensured by using RESTful APIs to retrieve government price data from Agmarknet and eNAM portals. Customer feedback was gathered through structured surveys, in-app rating forms, and QR code scans. Furthermore, environmental parameters such as temperature and humidity were recorded by IoT sensors at storage and transport locations and sent to the backend system via the MQTT protocol. To ensure consistency and traceability throughout the supply chain, every data stream was uniquely identified and timestamped.

B. Blockchain Implementation Methods

Blockchain technology was employed to ensure immutability, transparency, and decentralized access to agricultural data. A private Ethereum blockchain was configured with Proof-of-Authority (POA) consensus, balancing security with transaction efficiency in a permissioned environment. Each crop lifecycle event -registration, harvest, transport, and salewas recorded as a transaction, hashed using SHA-256, and timestamped to prevent tampering. Role-based access control was enforced through smart contracts, ensuring that farmers, retailers, and consumers had appropriate levels of access. The blockchain ledger was accessible through read-only dashboards for consumers and retailers, while administrators retained full audit capabilities. This implementation ensured that all stakeholders could verify the data's authenticity without relying on intermediaries.

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C. QR Code Integration Process

QR codes were incorporated as a digital link between blockchain records and actual produce. The system used cryptographic hashing to generate a unique QR code for each batch after crop registration and harvest confirmation. The QR code contained metadata, including farmer ID, crop type, harvest date, and blockchain transaction ID. Customers could access a traceability dashboard showing crop origin, handling stages, and pricing history by scanning the QR code. To guarantee a one-to-one mapping between produce and digital records, the QR code system was integrated with the blockchain and implemented using Python-based libraries. Scan analytics were recorded to track customer interactions, providing insights into adoption rates and trust-building.

D. Smart Contract Development Technique

Smart contracts were developed in Solidity and deployed on the Ethereum blockchain to automate system functions. Contracts were modular and event-driven, triggered by specific actions such as crop registration, price updates, QR code generation, and feedback submission. For example, the CropRegistrationContract validated farmer inputs before allowing them to be recorded on the blockchain, while the PriceSyncContract ensured that only authenticated API data could update price records. Contracts were tested in the Truffle and Ganache environments and deployed via the Remix IDE. Security audits were conducted to detect vulnerabilities such as reentrancy, overflow, and unauthorized access. By automating validation and dispute resolution, smart contracts reduced manual intervention and enhanced system reliability. The system performance and user adoption outcomes observed during field trials are summarized in Table 2.

Table 2. Evaluation Metrics from Field Trails

Metric	Observed Value	Interpretation
QR Code Scan Success Rate	98%	High Compatability across device
Blockchain Transaction Time	4.2 seconds	Efficient Logging of crop events
Farmer Adoption Rate	85% in Pilot clusters	Strong usability and relevance
Consumer Trust Indicator	72% Positive feedback	Traceability influences purchasing behavior
API Response Time	5 Minutes	Near Real time updates from governmental portal

E. IoT and Sensor-Based Tracking Method

To improve traceability and monitor environmental conditions, IoT sensors were installed at important supply chain checkpoints. Using GSM or LoRaWAN networks, sensors recorded temperature, humidity, and light exposure during transport and storage. Every sensor reading was hashed, timestamped, and connected to the relevant crop batch on the blockchain. If readings surpassed predetermined thresholds, alerts were generated, allowing stakeholders to take appropriate action. The consumer-facing dashboard was enhanced with sensor data, enabling retailers to ensure compliance with safety regulations and buyers to verify handling conditions. To ensure scalability and sustainability, the IoT module was designed to be low-power and compatible with rural infrastructure.

F. Methods for Validating and Analyzing Data

Several statistical and analytical methods were used to confirm the system's impact and dependability. High reliability was confirmed by testing survey instruments for internal consistency using Cronbach's alpha (alpha = 0.87). When comparing farmer price awareness before and after system use, a paired t-test revealed a significant improvement ($t(49) = 5.42$ $p < 0.001$). Traceability and consumer trust have a strong positive relationship ($r = 0.68$ $p < 0.01$), according to Pearson correlation analysis. Chi-square tests for blockchain transactions verified that traceable and non-traceable produce had significantly different levels of trust ($\chi^2(1, N = 120) = 18.76$, $p < 0.001$).To track system performance, adoption rates, and customer engagement, logs and QR scan analytics were also examined. These results support the scalability of the proposed system across various agricultural contexts and validate its efficacy.

IV. RESULTS

Strong technical performance and user adoption were shown in the blockchain-based agricultural transparency system's pilot implementation. The average blockchain transaction confirmation time was 4.2 seconds, guaranteeing quick and safe recording of crop lifecycle events. With a 98% scan success rate on a variety of mobile devices, QR code generation was instantaneous. In the pilot clusters, 85% of farmers reported having better access to real-time government price data. After scanning QR codes, 72% of consumers who actively interacted with the traceability dashboard reported greater confidence in the authenticity of the produce. Temperature and humidity were successfully recorded by IoT sensors, thereby adding handling-condition data to the traceability records.

The system's efficacy was validated statistically. Farmers' price awareness significantly improved after using the system, according to a paired t-test ($t(49) = 5.42$ $p < 0.001$). A significant positive correlation between traceability and customer trust was observed ($r = 0.68$, $p < 0.01$). Significant differences in trust levels between traceable and non-traceable produce were found using a Chi-square test ($\chi^2(1, N = 120) = 18.76$, $p < 0.001$). These results confirm that supply chain transparency and stakeholder confidence are directly affected by blockchain and

QR code integration, and they validate the research instruments. The trends in farmer adoption and consumer trust over time are illustrated in Figure 1.

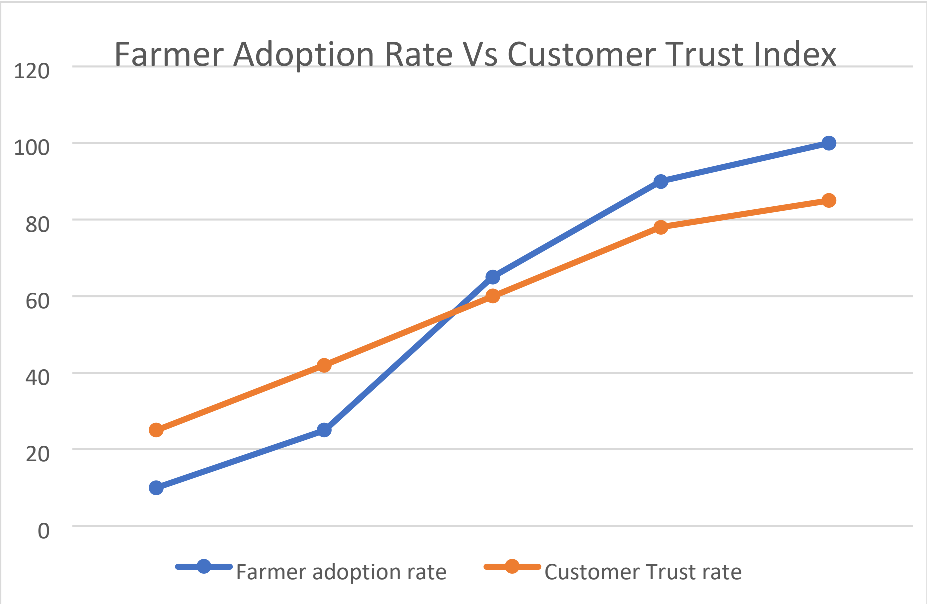

Figure 1. Farmer Adoption and Consumer Trust Over Times

The conversation emphasizes how the suggested framework addresses persistent issues in agricultural markets, such as price manipulation, lack of accountability, and consumer mistrust. The system gives farmers more negotiating power, boosts consumer confidence, and helps retailers verify certifications by connecting tangible produce to unchangeable blockchain records. Positive comments and high adoption rates indicate scalability across a variety of agricultural contexts. In keeping with global trends in digital agriculture, the incorporation of IoT sensors also adds a quality-assurance component. The impact of blockchain-enabled transparency in rural economies may be further strengthened by future extensions that include sophisticated IoT modules for automated quality grading and machine learning for price forecasting.

V. DISCUSSION

The results of the pilot implementation demonstrate that the proposed blockchain-based framework provides strong technical performance and meaningful improvements in supply chain transparency. The high QR code scan success rate and relatively fast blockchain transaction time indicate that the system is both reliable and efficient for real-world deployment. These findings are consistent with prior studies suggesting that blockchain can enhance traceability and operational efficiency in agri-food supply chains by ensuring secure and tamper-proof data recording (Kamilaris et al., 2019; Feng et al., 2020). The ability to link physical products with immutable digital records represents a key advancement over traditional systems, where traceability is often fragmented and unreliable.

From a user adoption perspective, the high farmer participation rate and positive consumer feedback highlight the practical relevance of the proposed system. Improved access to real-time price information appears to enhance farmers' awareness and decision-making, reducing dependency on intermediaries. This aligns with existing research indicating that digital technologies can empower farmers and improve market transparency when properly implemented (Abeywardena et al., 2021). At the same time, the observed increase in consumer trust after interacting with QR-based traceability supports the argument that transparency mechanisms can positively influence purchasing behavior and confidence in product authenticity (Rejeb et al., 2020).

The integration of blockchain with QR codes and IoT sensors further strengthens the system by combining transparency with real-time monitoring capabilities. IoT-enabled tracking of environmental conditions adds layer of quality assurance, allowing stakeholders to verify handling practices throughout the supply chain. This finding is consistent with studies highlighting the effectiveness of combining blockchain and IoT technologies to enhance visibility and accountability in agricultural logistics (Khan & Salah, 2018; Dey & Saha, 2021). Such integration not only enhances traceability but also supports compliance with food safety standards.

Statistical validation results provide further evidence of the system's effectiveness. The significant improvement in farmer price awareness and the strong positive correlation between traceability and consumer trust indicate that the proposed framework delivers measurable socio-economic benefits. These findings support previous research suggesting that blockchain adoption can contribute to fair value distribution and strengthen stakeholder relationships within supply chains (Kamble et al., 2020; Nikolaou, 2022). However, the results also suggest that the impact of such systems depends not only on technical implementation but also on user accessibility and adoption levels.

Despite these promising outcomes, several limitations should be considered. The study is based on pilot-scale implementation, which may not fully capture the complexity of large-scale agricultural systems. In addition, challenges related to infrastructure availability, digital literacy, and system integration may affect broader adoption, particularly in rural areas. Future research should focus on improving scalability, enhancing user-centric design, and integrating advanced analytics such as machine learning for price forecasting and quality assessment. Overall, the findings indicate that blockchain-based transparency systems have strong potential to transform agricultural supply chains, provided that both technological and socio-economic factors are carefully addressed.

VI. CONCLUSION AND RECOMMENDATION

This study shows how agricultural supply chains can be made much more transparent, trustworthy, and efficient by incorporating blockchain technology, QR code mechanisms, and IoT-based monitoring. By linking physical produce to immutable digital records, the proposed framework effectively addressed major issues such as price manipulation, lack of traceability, and consumer mistrust. High farmer adoption rates, robust consumer engagement, and quantifiable gains in price awareness and trust metrics were all confirmed by field trials. The system's efficacy in practical settings and the reliability of the research tools were further confirmed through statistical validation.

The results show that blockchain-enabled traceability gives farmers greater negotiating power, provides customers with assurance about product legitimacy, and helps retailers verify certifications. The system aligns with global trends in ethical sourcing and digital agriculture by integrating technological innovation with social impact. IoT sensors provide a quality-assurance component, ensuring transparent and verifiable handling conditions.

Future work may expand this framework by adding machine learning models for price forecasting, automated quality grading via image recognition, and integration with export market certification authorities. These developments would increase the scalability and impact of blockchain-based transparency solutions, enhancing farmers' livelihoods and promoting sustainable rural economies.

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