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AgroTrustX: An Integrated Blockchain and IPFS Framework for Secure Agricultural Data and Supply Chain Traceability

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***Abstract*—Food fraud and transparency concerns are common in agricultural supply chains, especially where product information is not easily verified by consumers. AgroTrustX is a blockchain enabled framework for the enhancement of traceability from the farmer to the consumer. Each agricultural batch is given a unique Batch ID and QR code to be tracked with its details and flow through the supply chain. The system leverages smart contract technology to log batch ownership, timestamps, GPS information and handover events on the Avalanche Fuji blockchain. Big files like certificates, documents, product images are stored on IPFS and their CIDs are linked to the blockchain record. The QR-based process enables distributors and retailers to change ownership and add any available transport information including temperature, humidity, time and place to the batch. Consumers can scan the QR code to see the product's history and verify claims through Zero-Knowledge Proofs. A Trust Score is provided based on the available verified facts and with the inclusion of ownership history, transport details and supporting documents. This results in a transparent and verifiable approach to agricultural supply-chain traceability.**

***Index Terms*—smart agriculture, blockchain, supply chain traceability, smart contracts, IPFS, Zero-Knowledge Proof, QR code, trust score**

I. Introduction

Agricultural products go through some stages before they reach consumers. The stages are farmers, distributors, retailers, and transport processes. At these stages it can be difficult to trace and verify product information. This brings up issues of transparency, product authenticity and whether claims such as organic or farm fresh are truthful. AgroTrustX addresses this problem by leveraging blockchain to keep a verifiable record of a product's journey. Each agricultural batch is given a unique Batch ID and QR code. The information like crop details, GPS location, images, quality information and supporting documents can be provided by the farmer. As the batch progresses through the supply chain, smart contracts on the Avalanche Fuji Testnet record the ownership and relevant handover information.

Agriculture is one of the most important sectors of the economy and ensuring transparency in agricultural supply chains is gaining increasing importance. Current systems are based on centralized databases and paper records that may lead to manipulation of data, lack of traceability, and delayed verification. It is difficult for consumers to verify the origin, quality and transportation history of agricultural products.Agriculture is one of the most important sectors of the economy and ensuring transparency in agricultural supply chains is gaining increasing importance. Current systems are based on centralized databases and paper records that may lead to manipulation of data, lack of traceability, and delayed verification. It is difficult for consumers to verify the origin, quality and transportation history of agricultural products.

Blockchain provides an immutable record and IPFS is used to store larger files such as certificates, product images, and documents. QR codes link the physical product to its digital record, providing distributors, retailers and consumers access to relevant information. Zero-Knowledge Proofs also assist in verifying the selected claims without revealing any private data that is not required. The system offers consumers a Trust Score and verified product information to enable more informed decisions. The main contributions of AgroTrustX are: 1) the use of blockchain technology for traceability at the batch level; 2) the use of QR codes for product identification; 3) the use of IPFS for decentralized storage of documents; 4) the use of smart contract technology for the recording of ownership; and 5) the use of Zero-Knowledge Proofs to verify the correctness of the information without revealing any private information, all integrated in a single framework for agricultural supply

chain.

II. Related Work

Recent studies have investigated blockchain, federated learning, IoT, and artificial intelligence for different agricultural applications. These approaches address data security, privacy, monitoring, and decision-making, but they often focus on specific agricultural tasks rather than complete end-to-end product traceability.

Manoj et al. [1] proposed a blockchain-assisted trusted federated learning framework for smart agriculture that combines blockchain and federated learning for agricultural applications. Their work demonstrates the use of blockchain for authentication, provenance, and traceability of model updates. Shen et al. [2] proposed BAFL-SVM, which combines blockchain and federated learning for agricultural prediction. Their approach addresses data security and prediction while introducing additional computational requirements.

Idoje et al. [3] investigated federated learning for crop classification in decentralized smart-farm networks, reducing the need to centralize raw agricultural data. Aggarwal et al. [4] presented a resource-efficient federated learning approach for rice leaf disease classification over IoAT. Alasbali et al. [5] investigated IoT-UAV based resource management for smart agriculture using federated reinforcement learning.

Azevedo et al. [6] examined the use of blockchain for supply-chain traceability and discussed its role in improving the visibility of supply-chain events. Pang et al. [7] presented a survey of blockchain-based agricultural traceability and identified important evaluation aspects and challenges. El Hajji et al. [8] investigated the use of Hyperledger Fabric for optimizing agrifood supply chains.

Sharma et al. [9] presented a decentralized agri-food supply-chain framework using Ethereum blockchain and IPFS. Li et al. [10] proposed a privacy-preserving blockchain-based supply-chain traceability model. Ellahi et al. [11] provided a systematic review of blockchain-based frameworks for food traceability, highlighting the potential of blockchain for improving transparency and provenance.

Arade et al. [12] investigated a privacy-preserving ZK-STARK-based blockchain approach for the agricultural food supply chain. Kobelt et al. [13] benchmarked different implementations of Zero-Knowledge Proof systems, providing useful background for understanding ZKP performance and computational overhead. Yu et al. [14] discussed blockchain-based fresh-food quality traceability and dynamic monitoring.

These studies show the potential of blockchain, IoT, federated learning, and AI in agriculture, but they often focus on individual agricultural tasks. There is still a need for an end-to-end traceability framework that follows an agricultural product from the farmer to distributors, retailers and finally to the consumer.

AgroTrustX addresses this need by combining batch-level blockchain traceability, physical-to-digital identification via QR, ownership transfer via smart contract, document storage via IPFS, transportation information, and privacypreserving verification in a single agricultural supply-chain workflow.

These studies show that different technologies have been used to address individual agricultural challenges. However, there remains a need for a practical end-to-end framework that focuses on agricultural batch traceability, ownership tracking, decentralized document storage, QR-based access, and privacy-preserving verification. AgroTrustX focuses on this area by connecting these components into a single supply-chain workflow.

III. Problem Statement and Objectives

A. Problem Statement

Agricultural supply chains involve several participants and multiple handover stages. Without a shared and verifiable record, information about the origin, ownership, transportation, and supporting documents of a product can be difficult to verify. Consumers may also have limited access to reliable information about the products they purchase. Before the agricultural products reach the final consumer, they usually pass through several stages. These stages can be farmers, distributors, transportation providers, retailers and other middlemen. During this process, information about the origin, ownership, quality, transportation, and supporting documents of a product may be recorded by separate systems or manual methods. This poses a challenge of maintaining a consistent and verifiable history of an agricultural product throughout the entire supply chain. The main problems addressed by AgroTrustX are:

- **Food fraud** — Food fraud is an important issue in agricultural supply chains because it is not always easy for consumers to verify product information and claims. Evidence may be needed to support claims about product origin, quality, organic status or farm source. Without proper recording and linking of such information to the product, consumers may find it difficult to determine whether the claims made about an agricultural product are supported by reliable information. A traceable digital record can help to link product claims to batch information and supporting documentation.
- **Lack of transparency** — Agricultural products go through several participants before they arrive to consumers and every participant may store information separately. It can be hard to know where a product came from, who owns it, where it has been, and where it is now. Consumers may not have direct access to the information recorded in the previous steps of the supply chain. A shared and verifiable record can enhance transparency through saving the history of the batch and providing relevant information to authorized participants and consumers.
- **Inefficient verification** — Certificates, quality reports, product images and other supporting documents are critical to verify agricultural products. However, when these documents are kept separately or checked manually, the

verification process can be time-consuming and inefficient. It may also be difficult to know which document belongs to which agricultural plot. The process of verification can be more organized by linking the supporting documents to a unique batch identity process and it can also allow the relevant information to be accessed when required.

- **Complex logistics** — Agricultural products pass through various stages of farmers, distributors, transportation providers and retailers. Ownership and other information may need to be updated at each stage. It is hard to maintain correct records of these hand-overs when different participants are using different systems. If available, transportation information like location, temperature, humidity and duration can give additional information on how the product was handled during movement. Thus, a reliable shared record is needed to link the different supply-chain events and keep a consistent history of the agricultural batch.

B. Objectives

The main objectives of AgroTrustX are:

- To provide every agricultural batch with a unique identity using a Batch ID and QR code.
- To maintain a verifiable record of batch ownership and supply-chain events using blockchain and smart contracts.
- To use IPFS to store large supporting files such as certificates, images, and documents.
- To provide privacy-preserving verification of selected claims using Zero-Knowledge Proofs.
- To provide consumers with easy access to information about batch history, transport details, supporting documents, and a Trust Score.

IV. Proposed System

A. System Overview

AgroTrustX is a comprehensive end-to-end process linking the farmer, backend, blockchain, IPFS, distributors, retailers, transport information and the consumer verification. The process includes farmer registration and batch creation followed by ownership transfer and final consumer verification. The proposed system is structured in different layers in such a way that every component has its own functionality but is nevertheless connected to the whole supply-chain workflow. The farmer layer is responsible for creating the initial batch information and the backend layer is responsible for authentication, validation and communication between application services. Important ownership and transaction information is contained in the blockchain layer, while IPFS is used for larger supporting files. The supply-chain layer handles the batch movements between participants and the consumer layer provides access to the recorded product information. The complete architecture is shown in Fig. 1.

B. Farmer Registration and Batch Creation

First, the farmer himself registers to the system and generates a wallet. Then the farmer can upload information on the crop and batch, including GPS coordinates, images, quality information and supporting documents. This information is sent to the backend for processing. The batch creation process provides the first digital identity of the agricultural product and sets the beginning of its traceability history. The batch can be associated with information such as crop type, batch number, quantity, harvest information, quality details, farm location and other relevant information. You can also upload supporting images and documents for additional verification. After information processing, the batch is linked to the respective record in the blockchain and to the QR code.

C. Backend Processing

Backend: Authentication, role validation, and OTP verification. It further supports batch ID and QR-related processing and supports signing transactions for blockchain transactions. The backend serves as the link between the user interface, storage services, and blockchain elements. It takes the information submitted by the users, processes the requests and communicates with the required services. Role-based processing allows different participants such as farmers, distributors and retailers to perform operations associated with their roles. The backend can also take care of uploading documents to IPFS and associating the obtained CID with the specific batch information. It also provides a structured communication layer between the application and the blockchain services, which means users don't need to manage blockchain operations themselves.

D. Blockchain and IPFS

These large files like certificates, product images and supporting documents are uploaded on IPFS which generates Content Identifier (CID). Then a smart contract makes the batch. The Avalanche Fuji blockchain stores the associated CID, the Batch ID and the owner information. The blockchain transaction can be shown to provide a verifiable record of the operation. The proposed system uses blockchain and IPFS in a complementary manner. The blockchain contains critical batch and ownership information and IPFS is used for larger files that are not suitable for direct on-chain storage. When ownership changes, the smart contract registers the related transaction or event and updates the current owner. Linking the batch to the CID creates a link between the record on the blockchain and the supporting digital documents. This approach allows the system to retain a traceable relationship between the agricultural product and the associated evidence.

E. QR Code Generation and Verification

A unique QR code will be created for each agricultural batch. The QR code is linked to the Batch ID and offers a simple link between the physical product and its digital history. By scanning the QR code, the system will be able to identify the batch and verify the information associated with it. The

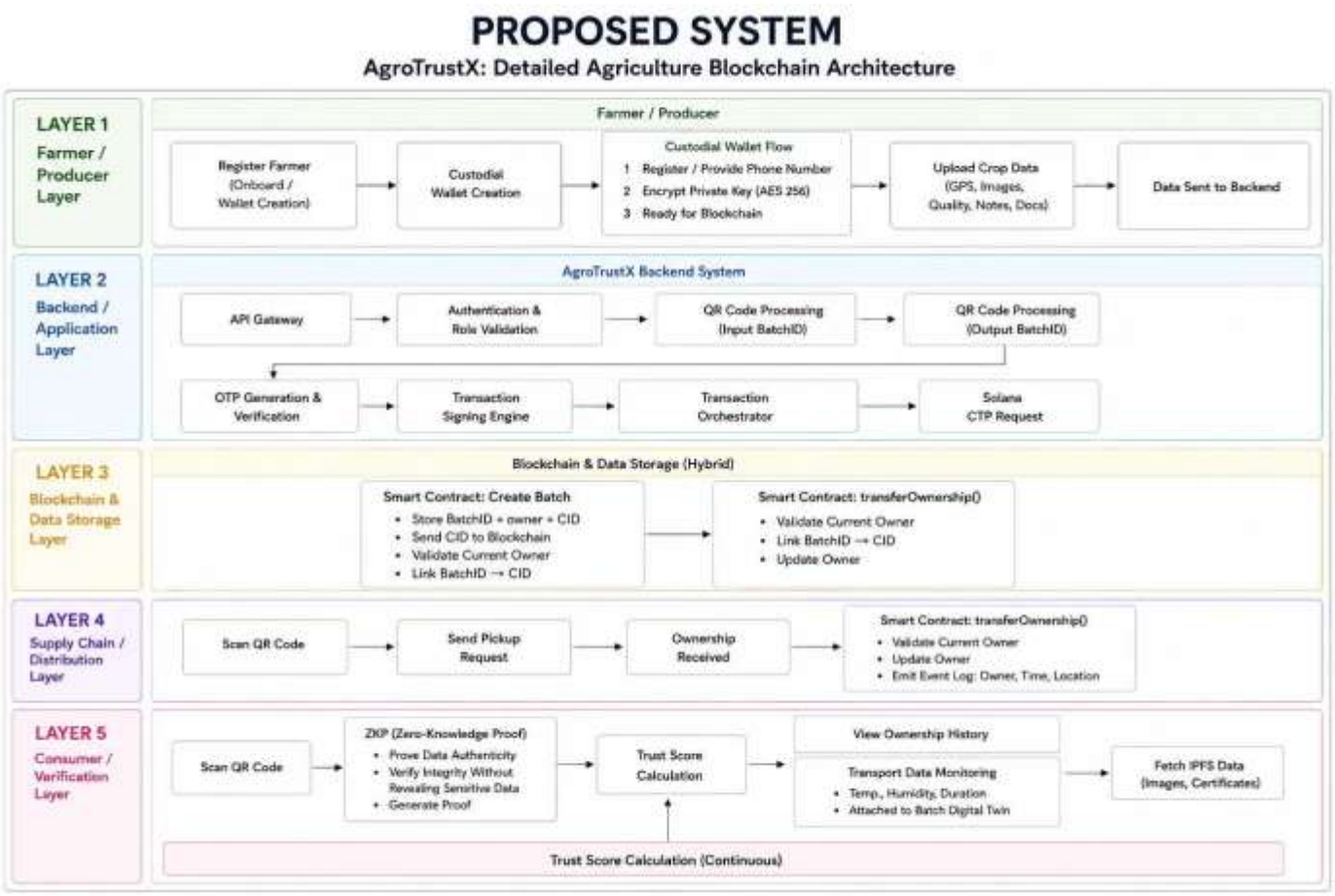

Fig. 1. Proposed AgroTrustX decentralized supply-chain architecture.

QR code can be read by different actors in the supply chain like distributors, retailers and consumers. Scanning the QR code helps supply-chain participants to identify the right batch before a pickup or ownership operation. At the consumer level, the same QR code is used to access the available product history and supporting information. This establishes a direct link from physical to digital and reduces the need for users to manually search for the corresponding batch record.

F. Distributor and Retailer

Distributors retailers can scan a batch QR code and generate a pick-up request. When the product is passed on to another participant, ownership is transferred by the smart contract. The new owner and the associated blockchain transaction or event are appended to the batch history. Ownership transfer helps to maintain a chronological record of the persons who have handled the agricultural product. During a handover, additional information such as location, GPS coordinates, time, price and notes can be added to the event if applicable. The farmer hands the batch to the distributor, who can then pass it on to the retailer. Similarly the batch information can be held by the retailer till it reaches the consumer. This gives you a complete history of ownership rather than just the current product owner.

G. Transport Information

Transport information can be attached to the corresponding batch as it progresses along the supply chain. Where implemented, information including temperature, humidity, transport duration and location are linked to the batch record. Such information provides additional insight into the circumstances and movement of the product during shipping. The information can be associated with a specific handover event, so that it remains tied to the corresponding batch. And GPS and location data can help to suggest where a particular supply-chain event occurred. Information on temperature and humidity can be useful for agricultural products that require controlled transportation conditions. This information is available in the present framework when implemented and provided. In future, integration with IoT sensors can allow for the automatic collection of these parameters during transport.

H. Consumer Verification

The traceability information of the product can be obtained by scanning the QR code at the consumer level. For relevant claims, we leverage Zero-Knowledge Proof verification, which enables verification without unnecessarily exposing the underlying private information. The Trust Score is calculated

using verified data we have on hand. The consumer can get information about the agricultural batch, such as product data, ownership history, available transportation data, images and supporting documents. The verification process gives consumers a way to check the information recorded along the supply chain. The ZKP component aims to provide an additional privacy preserving mechanism for certain claims. A claim can be verified based on the proof required, instead of revealing unnecessary underlying information. In this way, the consumer verification process can combine traceability information with privacy-aware verification.

I. Consumer View

The final consumer view will show the Trust Score as well as the ownership history and available transport information. Consumers can also see supporting IPFS content such as product images, certificates and documents. That lets consumers see where a product has been on its journey to them, before they buy it. The consumer interface combines information from various stages of the supply chain and presents it in a unified view. The information available may include Batch ID, product details, harvest information, current and previous ownership, quality information, transportation details and supporting documents. This provides the consumer with the opportunity to review the digital evidence available relating to the physical product, instead of just relying on the information provided at the point of sale. The Trust Score can be used to provide an overview of the available verified information, but the underlying records are available for further review.

V. IMPLEMENTATION

This section describes the main technologies and components used in the implementation of the AgroTrustX prototype. The implementation enables the agricultural supply-chain workflow by integrating the blockchain, IPFS, backend services, QR-code processing, ownership management, privacy-preserving verification, and application/database components.

A. Blockchain Implementation

The blockchain part of AgroTrustX was built and tested on Avalanche Fuji Testnet. The intelligent contracts based on Solidity manage important traceability operations such as creation of agricultural batches, ownership information and ownership transfer. Each agricultural batch is assigned a unique Batch ID, which enables the identification of its blockchain record along the supply chain. Relevant information is associated with the corresponding record in the blockchain when a batch is generated. Subsequent changes in the ownership are recorded as smart-contract transactions. The blockchain offers an auditable history of critical supply-chain functions and provides a record that can be shared and accessed during verification. This reduces reliance on individual stakeholders' separate records and allows for transparent tracking of the agricultural product from the farmer to distributors and retailers.

B. IPFS Integration

Instead of directly storing large files like certificates, product images, quality reports and supporting documents on the blockchain, these are stored on IPFS. IPFS creates a unique Content Identifier (CID) that can be linked to the particular agricultural batch when a file is uploaded. This way the amount of large data that has to be stored directly on-chain is reduced, but still there is a reference to the supporting information. The CID links the blockchain based batch record with the corresponding digital file. When needed the stored reference gives the users access to the related documents or images. So IPFS is complementary to blockchain in the sense that it deals with larger files and blockchain deals with valuable batch and transaction information. Combined, they provide a systematic way to link agricultural products to the digital evidence that supports them along the supply chain.

C. Backend and Authentication

The backend handles user authentication, role validation, OTP verification, and transaction-related operations in the AgroTrustX application. It takes data submitted through the application and orchestrates communication between the user interface, IPFS storage, database, and blockchain services. Role-based processing enables the use of functions by various participants, such as farmers, distributors, retailers, and consumers, that are relevant to their responsibilities. During the creation in batch mode, the backend will handle the submitted agricultural information and coordinate the storage and blockchain operations. It also offers support for processing and handling transactions related to QR-codes. The backend serves as a communication layer in between that simplifies user interaction with the underlying blockchain and storage components. This architecture enables efficient management of application-level operations while maintaining essential traceability information via blockchain and relevant digital files via IPFS.

D. QR Code Integration

A unique QR code is assigned to each registered agricultural batch that is linked to its corresponding Batch ID. The QR code allows a convenient link between the physical agricultural asset and its digital record in the AgroTrustX system. Supply chain actors scan the QR code to identify the correct batch for pickup, handover or other ownership activities. Consumers can also scan the same QR code and view the available information associated with the product. The QR-based mechanism eliminates the need for users to type in or search for batch IDs and offers a convenient way to access traceability information. The QR code allows the user to access relevant batch information, ownership details, transport history available, product images, certificates, and supporting documentation. This provides a consistent physical-to-digital identification mechanism across the various stages of the agricultural supply chain.

E. Ownership Transfer

When a batch of agricultural product is transferred between authorized participants in the supply-chain, the ownership transfer is handled via the smart contract. The process enables the current owner to transfer the batch to another participant and the updated ownership information is added to the traceability history of the batch. A batch may be transferred from a farmer to a distributor, and then from the distributor to a retailer. Each transfer can be linked to relevant information such as previous owner, new owner, timestamp, location, GPS coordinates, price and handover details where available. Recording the events provides a chronological history of the movement and ownership of the agricultural product. The smart contract based approach helps in maintaining consistency of the blockchain records and ownership change. Therefore, the system can provide a verifiable trail of the agricultural batch movement among different participants.

F. Zero-Knowledge Proof Verification

The Zero-Knowledge Proof (ZKP) component is designed to enable privacy-preserving verification of certain agricultural claims, without revealing the underlying private information unnecessarily. Instead of disclosing sensitive data , you can provide a proof that a given condition or claim is met . This technique can be useful when data needs to be verified by another participant while maintaining the privacy of the original data. The ZKP-based verification is linked to the consumer verification stage in AgroTrustX, where specific claims can be verified without the need for full disclosure of the underlying information. The mechanism gives an additional privacy layer on top of traceability and document verification via the blockchain. The goal is to enable users to get meaningful verification while not unnecessarily disclosing sensitive data. The ZKP element shall be presented according to its actual state of implementation in the final system.

G. Application and Database

AgroTrustX application offers role-based functionality for farmers, distributors, retailers and consumers. Farmers can register and submit agricultural batch information, and distributors and retailers can perform pickup and ownership-related operations. Consumers will be able to scan QR codes to access available information for a particular agricultural batch. A supporting database maintains a queryable, application-level record of batch and user information so that it can provide efficient access to frequently needed data. The application communicates with the backend, which is responsible for interaction with the blockchain and IPFS services. This combination enables the application to have a convenient user interface, while the blockchain keeps important traceability records and the IPFS keeps bigger supporting files. Therefore the database enables the application to function efficiently without substituting the blockchain record used for ownership and supply-chain verification.

VI. Results and Discussion

AgroTrustX was developed to demonstrate the traceability of agricultural products from the creation of the batch to the verification by the consumer as a working prototype. The suggested workflow of this work includes farmer registration, formation of agricultural batches, storage with IPFS, recording on blockchain, creation of QR-codes, transfer of ownership and available transportation information. The system links these operations through the backend and application tiers so that information created at different points of the supply chain can be linked to the proper batch. The results show the opportunities of combining the blockchain and the decentralized storage to keep the structured digital history of an agricultural product. The prototype also lays the groundwork for adding privacy-preserving verification and other advanced features to the agricultural supply-chain framework.

A. Batch Creation and Blockchain Recording

The batch creation process successfully associates a unique Batch ID with its owner and stored IPFS content. A farmer can create a new agricultural batch and associate information such as produce details, quantity, harvest information, location, quality details and supporting data. The corresponding transaction is executed through the smart contract and registered on the Avalanche Fuji blockchain. The record on the blockchain lets you identify the batch and who owns it now. Later ownership actions are associated with the same batch record. The process creates the first digital identity of the agricultural product and provides a basis for ensuring its traceability throughout the supply chain.

B. IPFS Storage

IPFS can be used to store product images, certificates, quality reports, and other supporting documents related to agricultural batches. Instead of storing large files directly on the blockchain, the system stores files through IPFS and gets the corresponding CIDs of the files. These CIDs can subsequently be linked to the respective blockchain batch record. This method keeps a reference to the supporting digital evidence while reducing the amount of big data that needs to be stored on-chain. The stored CID can be used to retrieve the corresponding file when verification is needed. Therefore, the integration of IPFS and blockchain provides a feasible solution for associating the agricultural batches with their supporting documents and digital evidence.

C. QR-Based Traceability

The QR-based method establishes a direct correlation between the physical agricultural batch and its digital twin. Each registered batch is assigned a QR code, which is associated with its unique Batch ID. The QR code can be scanned and the system can identify the corresponding batch and retrieve its available supply-chain information. Distributors and retailers can use the QR code to identify the correct agricultural batch during the pickup and handover operations. Consumers can also scan the same code to get related information of the

product. This includes available batch information, owner information, transport records, images and supporting documents. The QR mechanism thus provides a simple and easily accessible way of linking physical agricultural products with their digital traceability records.

D. Ownership Transfer

The smart contract records the transfer of ownership when an agricultural batch is transferred from one participant to another in the supply chain. The process permits the current holder to transfer the batch to an authorized participant such as a distributor or retailer. If the transfer is successful, the new owner is attached to the batch and the transaction is added to the traceability history of the product. Transfer can also carry with it other handover information like timestamp, location, GPS coordinates, price and notes where available. The retention of these ownership events provides a time sequence record of the movement of the agricultural commodity. This makes the different participants involved in handling the batch more visible and allows for verifying the supply-chain history of the batch later on.

E. Privacy Verification

The Zero-Knowledge Proof module is intended to facilitate verification of selected claims without unnecessarily revealing the underlying private information. Instead of directly exposing complete information, a proof can be used to demonstrate that a particular condition or claim has been satisfied. This provides an additional privacy layer to the traceability framework and can be useful when sensitive information must remain protected. In the AgroTrustX architecture, privacy verification is associated with the consumer verification stage and can complement blockchain records and supporting documents. The approach allows relevant information to be verified while limiting unnecessary disclosure. The ZKP component should be reported according to its actual implementation and testing status in the final experimental evaluation.

F. Consumer Information

The last consumer interface is the access to the product information available collected through the entire supply chain. After scanning the QR code, consumers can check details such as Batch ID, product details, ownership history, harvest information, available transportation details, images, certificates and other supporting files. Where it is deployed, privacy-preserving verification can provide additional verification of selected claims, without exposing unnecessary private information. The consumer view combines information collected at various phases and displays it through a single interface. This enables consumers to verify the digital history of an agricultural product before purchase. The system thus encourages access to supply-chain information and provides a more structured view of the product's documented journey from source to consumer.

G. Quantitative Evaluation

To complement the functional evaluation, the execution time of the major AgroTrustX operations can be illustrated with the illustrative values below. These are the values of the quantitative evaluation format used during prototype analysis. These values should be replaced with actual measured values before final conference submission.

The average execution time is calculated using:

$$T_{\text{avg}} = \frac{1}{N}\sum_{i=1}^{N} T_i \quad (1)$$

where T_i represents the execution time of the i-th observation and N represents the total number of observations.

The standard deviation of the execution time is calculated using:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(T_i - T_{\text{avg}})^2} \quad (2)$$

The transaction success rate is calculated as:

$$\text{Success Rate} = \frac{\text{Successful Transactions}}{\text{Total Transactions}} \times 100 \quad (3)$$

For example, if 98 out of 100 transactions are successfully completed, the success rate is:

$$\text{Success Rate} = \frac{98}{100} \times 100 = 98\% \quad (4)$$

The throughput of the system can be calculated as:

$$\text{Throughput} = \frac{\text{Total Transactions}}{\text{Total Execution Time}} \quad (5)$$

For example, if 100 transactions are completed in 284 seconds:

$$\text{Throughput} = \frac{100}{284} \approx 0.35 \text{ TPS} \quad (6)$$

The scalability increase can be represented as:

$$\text{Scalability Increase} = \frac{T_{\text{baseline}} - T_{\text{scaled}}}{T_{\text{baseline}}} \times 100 \quad (7)$$

The illustrative quantitative values are presented in Table I.

TABLE I
ILLUSTRATIVE QUANTITATIVE EVALUATION OF AGROTRUSTX

Operation	Avg. (s)	Std. Dev. (s)	Success (%)
Batch Creation	2.84	0.29	98
Ownership Transfer	2.61	0.27	98
IPFS Upload	3.17	0.38	100
IPFS Retrieval	1.18	0.16	100
QR Verification	1.42	0.19	98
ZKP Verification	1.76	0.21	100

The graph in Fig. 2 provides The average execution time of the major operations is visually compared The IPFS upload is the most time-consuming and has the highest illustrative execution time among the evaluated operations. The IPFS retrieval uses relatively less time.

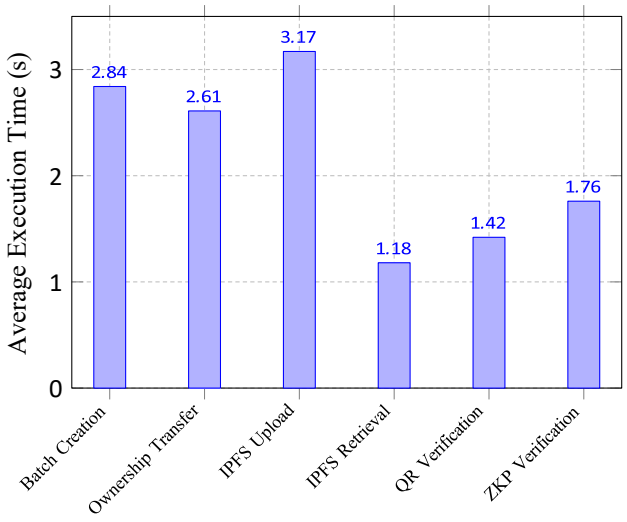

Fig. 2. Illustrative average execution time of AgroTrustX operations.

H. Discussion

The AgroTrustX prototype demonstrates an integrated approach to improve traceability and transparency in an agricultural supply chain. The implemented workflow connects the major stages of the product journey, starting from the farmer registration and batch creation, going through the blockchain recording, IPFS based document storage, QR code generation, ownership transfer, transport information and consumer verification. The system connects these components to create a digital representation of an agricultural batch that can be referenced as it moves through different supply-chain participants. This approach solves the problem of maintaining consistency of product information, as farmers, distributors, retailers and consumers would otherwise be using different records or checking information manually.

Blockchain is an important technology to keep the traceability and ownership history of the agricultural batch. Smart agreements are able to store such information as the batch creation and ownership transfers during its lifetime, hence the current owner and its transactions can be associated with the batch. This means they can have one record that different participants can refer to. IPFS supports the blockchain by providing storage for larger supporting files such as product images, certificates, quality reports and other documents. Instead of storing large files directly on-chain, the batch record can refer to the corresponding Content Identifier. This connects the verifiable blockchain record with the supporting digital evidence.

The QR-code mechanism offers a practical link between the physical agricultural product and its digital identity. Distributors and retailers can use the QR code during handover operations and consumers can scan the same code to view the available product information. The records of ownership transfers also help traceability as they track the movement of the batch between different stakeholders. Transport related information including temperature, humidity, duration and location can be associated with the batch whenever such information is available.

The Zero-Knowledge Proof component is an additional privacy-preserving solution for certain verification requirements. This could enable verification of claims without unnecessarily revealing the underlying private information. However, the privacy and computational performance of this component depends on its actual implementation status, and further experimental evaluation is needed. Similarly, the Trust Score should be understood as an indicator of available and validated information, not as a guaranty of the authenticity of a physical product.

To summarize, AgroTrustX offers a basis for integrating blockchain, IPFS, QR-based identification, ownership tracking and privacy-aware verification. Further experiments with real measurements are needed to evaluate latency, transaction success rate, throughput, scalability, storage performance and practical usability under larger workloads.

VII. Limitations

The current AgroTrustX implementation is a prototype and has not been evaluated at large production scale. Its operation depends on blockchain and IPFS infrastructure as well as reliable internet connectivity. Transport information such as temperature, humidity, duration, and location is available only when the corresponding data is implemented and provided. Zero-Knowledge Proof verification also introduces additional computational requirements compared with basic data verification.

Further testing with a larger number of users, batches, and transactions would be required to evaluate the scalability and performance of the system in a real agricultural supply chain. A usability test with actual farmers, distributors, retailers, and consumers is also recommended to fully appreciate the system's practical usability.

VIII. Future Scope

The future development of AgroTrustX can be devoted to improving the scalability, usability, security, privacy, and real-world agricultural supply chains applicability of the system. One of the major extensions is the use of monitoring devices based on the Internet of Things (IoT). The existing framework is capable of linking transportation data, like temperature, humidity, duration, and location, with an agricultural batch when such data is available. These parameters can be automatically captured during transportation and storage by means of IoT sensors in future implementations. The sensor-produced information can then be linked to the respective batch and supply-chain event. It can reduce reliance on manually entered transportation information and provide more ongoing tracking of agricultural products.

Another important area is large scale performance evaluation and deployment. The current prototype shows the main workflow; however, real agricultural supply chains can have many more farmers, batches, transactions, distributors,

retailers, and consumers. Future experiments can then validate the system with increasing workloads and measure transaction latency, throughput, IPFS upload and retrieval time, QR verification time, storage requirements, transaction costs and overall success rates. Experiments of this nature help to reveal scalability limitations and determine the requirements for production deployment outside of the testnet environment.

The Zero-Knowledge Proof module can be further developed and evaluated as well. Future work can implement full proof-generation and verification workflows for selected agricultural claims and measure their computational overhead. Various verification scenarios can be explored to see how privacy can be preserved while also offering meaningful evidence to consumers and supply-chain participants.

The system can also be improved by mobile applications and multilingual support. A mobile interface can ease QR scanning, batch registration, document uploading, ownership operations and consumer verification. Multilingual features may improve the usability of the system for farmers and other users who prefer to work in different languages.

In future work, the integration of agricultural certification system, logistics services, regulatory platform and other agricultural information systems may be explored. Additional types of certification can be incorporated to improve product verification. The proposed Trust Score can be further improved based on clearly defined and experimentally validated criteria, while keeping the distinction between the availability of evidence and the authenticity of physical products clear. Finally, it is possible to carry out field testings with real agricultural stakeholders to assess usability, security, reliability and operational requirements. These developments can further facilitate the transition of AgroTrustX from a prototype to a more comprehensive and practically deployable agricultural traceability framework.

IX. Conclusion

Agricultural supply chains require reliable methods for tracking products and verifying their information. AgroTrustX addresses this challenge by combining blockchain, smart contracts, IPFS, QR codes, and Zero-Knowledge Proofs into a single traceability framework.

Each agricultural batch receives a unique identity and can be tracked through ownership changes from the farmer to the consumer. Supporting documents and images are stored on IPFS, while important batch and transaction information is recorded on the Avalanche Fuji blockchain. QR codes provide a simple way to access the digital record associated with a physical product. The consumer interface provides access to the Trust Score, ownership history, available transport information, and supporting documents. By combining transparent record keeping with privacy-preserving verification, AgroTrustX provides a practical approach to improving traceability and trust in agricultural supply chains.

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