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AgriChain: A Blockchain Based Smart Farm SupplyChain System

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Abstract— ***In today's fast moving world, agricultural supply chains face data tampering/loss of trust and transparency as well as ineffective traceability. These challenges arise from the use of traditional centralized systems which do not guarantee immutability or have proper ownership tracking which results in product fraud, degraded product quality and ineffective logistics. This paper proposes a framework for a decentralized agricultural supply chain called AgriChain that leverages IoT (Internet of Things) sensors, decentralized storage, blockchain Smart Contracts and cryptographic verification to provide a secure, decentralized agricultural supply chain. The AgriChain Framework will use IoT sensors throughout the supply chain to collect environmental/crop data, generate secure hashes and build Merkle trees for data integrity. The sensor data will be stored on IPFS using Pinata, while only the immutable metadata (CID and Merkle root) will be posted to the Ethereum Sepolia Blockchain. Ownership transfer and state changes will be executed using the sequential Smart Contract method with the atomic transfer And Update State function. The AgriChain Framework will offer a user-friendly interface through a React frontend that provides real-time monitoring, visualizations of the agricultural supply chain over time and QR codes to verify purchases by consumers. Our experimental implementation demonstrates secure traceability, tamper-evident storage of data, and efficient transfer of ownership for all stakeholders involved in the agricultural supply chain. The proposed architecture can serve as an extensible, resilient foundation for future decentralized agricultural supply chain implementations.***

Index Terms— ***Blockchain, IoT, Smart Agriculture, Supply Chain, IPFS, Ethereum, Merkle Tree, Traceability.***

I. INTRODUCTION

Agriculture is an important part of our lives. It helps make sure we have food on our tables and supports the economy. As the worlds population grows we need to produce food. This means the process of getting food from farms to our plates becomes more complicated. Many people are involved, including farmers, truck drivers, storage facilities, distributors, retailers and consumers.

Even with new technology there are still many problems with the way food is moved from farms to stores. Some of these problems include not being able to track food, lack of honesty and difficulty in keeping food fresh. The old way of tracking food relies on one system, which can be controlled by one person or group. This makes it easy for someone to cheat or make mistakes. When this happens it can be hard to figure out where the problem started and it can lead to losses. New technologies like the Internet of Things (IoT) are helping to make farming smarter [2]. IoT devices can be placed on farms to monitor things like temperature, humidity and soil moisture [1]. This helps farmers grow crops. However it is still a challenge to make sure all the data from these devices is accurate and shared safely.

By providing a decentralized and unchangeable record of transactions, blockchain technology is quickly gaining popularity as a viable solution for trust-related issues in data management [6]. Blockchain ledger technology allows for transaction records to be distributed across the entire network so that any modification made to recorded data requires agreement among all other members of the network before it can occur [7]. The properties of blockchain ledger technology make this technology a good fit for supply-chain type applications because the ability to trace and verify all parties involved in a transaction is critical to their success. The fact that all players can independently verify the history of each product without relying on an intermediary is made possible by the fact that blockchain keeps a shared and immutable transaction history.

Despite its advantages, it is not practical to keep massive IoT datasets directly on a blockchain network because of very high storage costs, limited scalability and transaction overhead. Hybrid solutions that utilize both blockchain and decentralized storage methods have begun to be explored in order to address these issues [5]. An example is the InterPlanetary File System (IPFS), which enables the storage of large datasets offchain while maintaining cryptographic references on-chain. By doing so, the costs associated with storing on blockchain will be greatly reduced, while at the same time allowing for both data integrity and authenticity.

The use of cryptographic techniques, such as Merkle trees, allows for the efficient aggregation and validation of an enormous number of transactions by creating a single root hash for many individual transaction entries [8]. By anchoring the Merkle root onto the blockchain, companies can verify the authenticity of the entire aggregate set of

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transactions without needing to store all individual transactions on the blockchain [9].

Agricultural supply chains also need a way to track who owns the food and what state it is in as it moves through the system. Smart contracts, which are like automated rules can be used to make sure everything happens in the order and that ownership is transferred correctly. This reduces the need for intervention and increases trust.

Motivated by these challenges, this paper proposes AgriChain, a decentralized IoT-based agricultural supply-chain system that integrates IoT sensing, blockchain technology, decentralized storage, and cryptographic verification mechanisms. The proposed framework collects sensor data from farm environments, generates secure hashes, and constructs Merkle trees to guarantee data integrity. Complete datasets are stored on IPFS, while only lightweight references including content identifiers and Merkle roots are anchored on the Ethereum blockchain. A smart contract enforces sequential supply-chain progression through an atomic ownership-transfer mechanism, ensuring consistency and preventing unauthorized state changes [10]. Additionally, a web-based frontend enables stakeholders and consumers to visualize supply-chain progress and verify product authenticity using QR-code-based access [6].

The main goal of AgriChain is to establish a transparent, secure, and scalable infrastructure for agricultural traceability while minimizing blockchain overhead. Unlike traditional supply-chain systems that rely heavily on centralized authorities, the proposed solution distributes trust across participants, allowing independent verification of product history. The system also shows how IoT-generated agricultural data can be securely integrated with decentralized technologies to build a reliable ecosystem for smart farming and food safety.

The key contributions of this work are summarized as follows:

- Design and implementation of a decentralized agricultural supply-chain architecture integrating IoT, blockchain, and IPFS.
- Application of Merkle tree–based hashing to ensure efficient and verifiable sensor data integrity.
- Development of smart contracts enforcing sequential ownership transfer and state transitions.
- Implementation of a hybrid on-chain/off-chain storage model to optimize scalability and transaction costs.
- Development of a consumer verification interface enabling transparent product validation through blockchain records.

By combining IoT sensing with decentralized trust mechanisms, AgriChain aims to bridge the gap between smart agriculture and secure supply-chain management, offering a practical solution for improving transparency, accountability, and confidence in agricultural ecosystems.

II. RELATED WORK

A. Blockchain-Based Agricultural Traceability Systems

Many research projects have looked at how blockchain systems can help improve the traceability of products in food supply chains [6]. The main aim of these systems is to create permanent record of the movement of food items from farms all the way to purchase by consumers, which will allow for greater transparency and will eliminate much of the fraud out of food supply. The block chain traceability frameworks, therefore, provide permanent records of transaction metadata, such as where the food originated, how it was transported, and who owned it, which are maintained across distributed ledger. By removing central control in the distribution of food, block chains allow for greater trust between players in the supply [7] and give consumers more assurance that they are purchasing a legitimate product.

While a lot of the initial blockchain projects concentrated on recording transactions instead of integrating sensors and sensor data securely in a live environment, there were numerous examples where members of the supply chain had to enter data into the blockchain manually which added a margin of error and reduced automation. Also, because the blockchain networks have to store large amounts of data, increased storage costs will continue to be a major barrier to successful implementation of blockchain technology.

B. IoT-Driven Smart Agriculture Monitoring

The use of IoT technology has revolutionized modern agricultural practices by providing access to real-time monitoring of environmental parameters and crop health [1], enabling farmers to utilize sensor networks on their farms to obtain data about temperature, relative humidity, soil moisture content, nutrient status, etc [2]., as well as abnormal conditions in their environment. With this information in hand, farmers now have the capability to manage resources more efficiently and produce higher yield from their crops.

Although traditional IoT-based agricultural technologies are effective, they use a highly centralized approach to store and analyze data on cloud platforms. This architecture can lead to security vulnerabilities from unauthorized modification of data, the presence of single points of failure within the system, and limited visibility of the data collection process among stakeholders in the supply chain. Additionally, data sharing within the supply chain typically does not utilize standardized verification mechanisms, which may ultimately affect how much trust a farmer has in the data that is collected. These limitations suggest that agricultural systems require decentralization to ensure data integrity and to securely share that data.

C. Blockchain and IoT Integration in Supply Chains

In order to solve the trust and security issues associated with using traditional centralized IoT architectures, many researchers have tried to create a solution by combining the

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two technologies blockchain and IoT devices [7], [10]. These new architectures utilize cryptographic signatures from IoT devices to generate a blockchain record of the data to create a tamper-proof record of the condition of a product while it is being transported and stored. This combination improves the accountability of companies that do business together and gives them real-time visibility into their collective supply chain processes.

Although many existing IoT systems with these types of architectures have attempted to directly store IoT sensor streams in a blockchain, they have failed because of the high volume of data generated and the low volume of blockchain transactions. Many of the current systems have either reduced the granularity of the data that they created or only stored summarized data, which does not provide the level of verification needed for professionalism. Furthermore, there are no existing frameworks to ensure that the sequential transfer of ownership happens continuously or that the state of any given product will be controlled and transferred in a timely manner. These problems create inconsistencies throughout an entire supply chain workflow.

D. Decentralized Storage and Data Integrity Approaches

To overcome blockchain scalability limitations, decentralized storage platforms such as IPFS have been proposed as complementary solutions. In hybrid architectures, large datasets are stored off-chain while blockchain records only cryptographic references or content identifiers [5]. This approach significantly reduces storage costs while preserving immutability through hash-based verification.

There is also a significant amount of research regarding the ability of Merkle trees (cryptographically secure data structures) to facilitate efficient integrity validation [8]. By storing multiple separate records within a single root hash, you can perform an efficient verification of the entire collection of data records using a lightweight verification process without retrieving each individual record from the dataset. While Merkle trees have been widely used for many blockchain applications, their use in agricultural-related IoT supply chainrelated systems is still relatively minimal [9]. The majority of current implementations do not utilize Merkle-based verification for the aggregation or validation of sensor data.

E. Smart Contracts for Supply Chain Automation

Smart contracts have been increasingly adopted to automate supply-chain operations by enforcing predefined business rules [6]. These programmable contracts enable automatic execution of transactions such as ownership transfer, payment validation, and state updates. In agricultural contexts, smart contracts can ensure that products move through predefined stages including harvesting, transportation, storage, and delivery [10].

However, several existing solutions implement ownership transfer and state updates as separate transactions, resulting in operational complexity and potential inconsistencies. This separation may require multiple participants to perform sequential actions manually, reducing system efficiency and increasing the risk of synchronization errors.

F. Research Gaps Identified

A review of the current literature uncovers multiple significant deficiencies:

- Limited integration of real-time IoT data with blockchainbased verification mechanisms.
- Inefficient handling of large sensor datasets due to excessive on-chain storage.
- Lack ofcryptographic aggregation methodsfor lightweight data validation.
- Absence of atomic mechanisms for secure ownership transfer and state progression.
- Insufficient consumer-level verification interfaces enabling transparent product authentication

The proposed AgriChain framework addresses these limitations by combining IoT sensing, decentralized storage, blockchain anchoring, and cryptographic verification into a unified architecture

III. METHODOLOGY

A. System Design Overview

The methodology adopts a layered architectural model composed of four interconnected layers:

- IoT Data Acquisition Layer
- Backend Processing and Integrity Layer
- Blockchain Validation Layer
- Application and Verification Layer

B. IoT Data Acquisition Layer

The IoT layer is responsible for collecting real-time environmental parameters related to crop cultivation and post-harvest handling. In the prototype implementation, sensor data is simulated to represent realistic agricultural conditions; however, the architecture supports direct integration with physical IoT hardware such as ESP32-based sensor nodes.

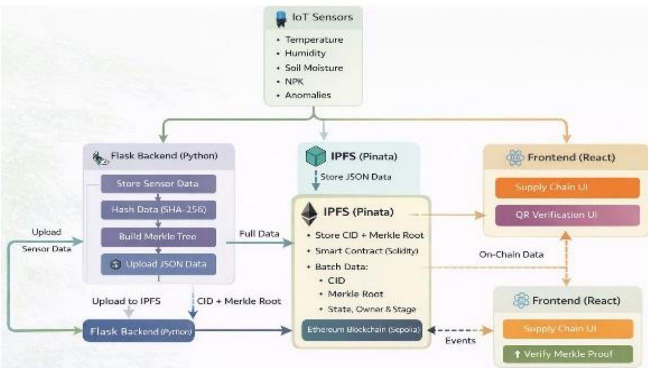

Fig. 1. Architecture of the proposed AgriChain System

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The monitored parameters include:

- Temperature
- Humidity
- Soil moisture
- Nutrient concentration (NPK values)
- Anomaly detection indicators

Each sensor reading is associated with a timestamp and a unique batch identifier to maintain chronological consistency. Data collection occurs periodically, enabling continuous monitoring throughout the supply-chain lifecycle.

The objective of this layer is to generate reliable and verifiable data that can be securely shared among all stakeholders.

C. Backend Processing and Data Integrity Layer

The backend layer, implemented using the Flask framework, acts as an intermediary between IoT devices, decentralized storage, and blockchain infrastructure. This layer performs multiple processing operations to ensure authenticity and efficient data handling.

- Data Hashing:

Upon receiving sensor readings, the backend generates cryptographic hashes using the SHA-256 algorithm [5]. Each data entry is converted into a deterministic hash value representing its contents. Any modification to the original data results in a different hash, enabling tamper detection.

- Merkle Tree Construction:

To efficiently handle multiple sensor records, AgriChain organizes individual hashes into a Merkle tree structure [8]. The process includes:

– Generating hashes for all sensor records
– Pairwise combination of hashes
– Recursive hashing until a single root hash is produced

The resulting Merkle root serves as a compact cryptographic representation of the complete dataset. This significantly reduces verification complexity since only the root hash must be stored on-chain.

- Data Packaging:

Sensor readings, metadata, and generated hashes are combined into a structured JSON format. This package represents the immutable dataset associated with a specific agricultural batch.

D. Decentralized Storage Methodology

Direct storage of large datasets on blockchain is inefficient due to scalability and cost limitations. Therefore, AgriChain adopts decentralized storage using [5].

The backend uploads the finalized JSON dataset to IPFS through Pinata integration. After upload, IPFS generates a unique Content Identifier (CID) derived from the file's cryptographic hash [7].

This methodology provides several advantages:

- Large datasets remain off-chain, reducing blockchain costs
- Data immutability is guaranteed through content-based addressing
- Distributed storage improves availability and resilience

Only the CID and corresponding Merkle root are forwarded to the blockchain layer for permanent anchoring.

E. Blockchain Validation Layer

The blockchain layer ensures trustless verification and secure supply-chain state management. Smart contracts deployed on the Ethereum Sepolia network maintain essential metadata associated with each agricultural batch [6].

- Batch Registration: After IPFS upload, the backend invokes the smart contract to register the batch. The following information is stored:

– Batch identifier
– IPFS CID
– Merkle root
– Farmer address
– Current owner
– Supply-chain state

This creates an immutable linkage between decentralized storage and blockchain records [10].

- Sequential Supply Chain State Management AgriChain enforces predefined supply-chain stages:

– Harvested
– In Transit
– In Cold Storage
– Delivered
– Rejected

State transitions must occur sequentially to prevent invalid or unauthorized updates.

- Atomic Ownership Transfer:

Ownership transfer and state progression are combined into a single smart-contract function: transferAndUpdate State(batchId, newOwner, newState) This atomic operation ensures that ownership updates and stage transitions occur within one transaction, preventing inconsistencies and improving user experience.

F. Application and Verification Layer

The application layer provides interfaces for both supplychain stakeholders and end consumers.

- Stakeholder Interface: The React-based frontend enables users to:

– Create and manage agricultural batches
– Monitor supply-chain progress
– Transfer ownership
– Update product states
– View blockchain transaction details

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Blockchain interaction is handled through Ethers.js integration.

- Consumer Verification Mechanism:

Each batch generates a QR code linked to blockchain metadata. When scanned:

- Batch information is retrieved from blockchain
- Sensor data is fetched from IPFS
- Merkle root comparison verifies data integrity

This mechanism allows consumers to independently verify product authenticity without relying on centralized authorities.

IV. HARDWARE COMPONENTS

The AgriChain system utilizes IoT hardware components to collect agricultural environmental data and enable realtime monitoring across the supply chain [2]. The architecture supports physical deployment using commonly available smart farming devices.

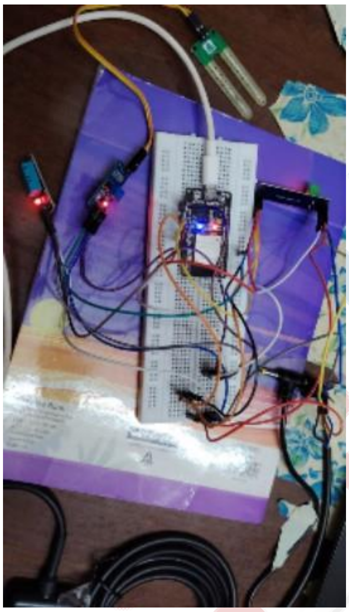

Fig. 2. Hardware Components of AgriChain

The hardware components of the AgriChain system include the following:

- **ESP32 Microcontroller:** The ESP32 serves as the central processing unit for data acquisition and communication.

It collects sensor readings and transmits data to the backend through Wi-Fi connectivity.

- **Temperature and Humidity Sensor:** This sensor measures atmospheric conditions that influence crop quality and storage safety. The collected data helps monitor environmental stability during different supply-chain stages.
- **Soil Moisture Sensor:** The soil moisture sensor measures water content in soil, enabling monitoring of irrigation conditions and cultivation quality.
- **NPK Sensor:** This sensor records soil nutrient levels including nitrogen, phosphorus, and potassium, providing insights into soil fertility and crop health.
- **Communication and Power Module:** Wireless communication is achieved using the ESP32's built-in Wi-Fi capability, while a regulated power supply or rechargeable battery ensures continuous operation.

Together, these components form the IoT sensing layer of AgriChain, enabling reliable data collection that supports secure blockchain-based traceability.

V. SOFTWARE ARCHITECTURE

The AgriChain software architecture is designed to provide secure data processing, decentralized storage, blockchain integration, and user interaction through a modular and scalable framework. The system combines backend services, blockchain smart contracts, decentralized storage, and a webbased frontend to ensure transparent and reliable agricultural supply-chain management.

- **Backend Layer:**

The backend is implemented using the Flask framework and acts as the core processing unit of the system. It receives IoT sensor data, performs data validation, and generates cryptographic hashes using the SHA-256 algorithm [5]. Multiple sensor records are aggregated into a Merkle tree to produce a single Merkle root representing the integrity of the entire dataset. The backend also manages communication with decentralized storage and blockchain services, ensuring smooth coordination between system components.

- **Decentralized Storage Layer:**

Large sensor datasets are stored using the InterPlanetary File System (IPFS) through Pinata integration. The backend uploads structured JSON data to IPFS and receives a unique Content Identifier (CID). This CID serves as a permanent reference to the stored data and allows retrieval without relying on centralized servers. Only the CID and integrity proofs are forwarded to the blockchain layer, reducing storage overhead.

- **Blockchain Layer:**

The blockchain layer consists of Solidity-based smart contracts deployed on the Ethereum Sepolia network [6]. Smart contracts maintain essential batch information such as ownership details, supply-chain state, IPFS references, and Merkle roots [10]. Sequential state transitions and ownership transfers are enforced through predefined contract logic, ensuring that supply-chain operations follow a secure and transparent workflow.

- **Frontend Application Layer:**

The frontend is developed using React and provides an interactive interface for stakeholders. Users can create batches, monitor supply-chain stages, transfer ownership,

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and verify product authenticity. Blockchain communication is handled using Ethers.js, enabling secure wallet-based transactions. The frontend also supports QRcode-based verification, allowing consumers to access blockchain records and IPFS data for transparency.

- **System Integration:**

All software components operate together to form an end-to-end decentralized platform. IoT data flows from sensors to the backend, is securely stored in IPFS, anchored on blockchain through smart contracts, and finally visualized through the frontend interface. This layered architecture ensures scalability, security, and efficient data verification across the agricultural supply chain.

VI. KEY IMPLEMENTATIONS

AgriChain is implemented as a hybrid IoT–blockchain architecture that ensures secure and tamper-proof agricultural supply chain tracking [7]. At the farm level, IoT sensors (simulated using ESP32) collect environmental data such as temperature, humidity, soil moisture, NPK values, and anomaly status. The Flask backend processes this data by generating a SHA-256 hash for integrity and constructing a Merkle tree from all sensor readings of a batch. The resulting Merkle root acts as a cryptographic fingerprint of the entire dataset. Instead of storing large sensor data directly on-chain, the complete batch metadata and readings are uploaded to IPFS via Pinata, and only the IPFS CID and Merkle root are anchored on the blockchain. This hybrid storage approach ensures scalability, reduces gas costs, and maintains verifiable data integrity.

On the blockchain side, the smart contract deployed on Ethereum Sepolia enforces strict supply chain workflow rules using a structured batch model that stores ownership, state, CID, and Merkle root. The system implements sequential state validation, ensuring that each stage (Harvested → In Transit → Cold Storage → Delivered/Rejected) progresses in order without skipping. A key implementation highlight is the atomic transferAndUpdateState function, which combines ownership transfer and state update in a single transaction, preventing inconsistent states and eliminating wallet-switching issues. The React frontend integrates wallet connectivity using Ethers v6, enabling batch creation, blockchain interaction, and QR-based consumer verification. When a product is scanned, the system retrieves on-chain data, fetches IPFS records, and validates the Merkle root, ensuring transparency, authenticity, and decentralized trust across the entire agricultural supply chain.

VII. ALGORITHMS

A. IoT Data Hashing and Merkle Root Generation Mechanism

This algorithm processes IoT sensor readings, generates cryptographic hashes, and constructs a Merkle tree to produce a single Merkle root representing the integrity of the entire dataset. The generated root is later anchored on blockchain for verification.

1: Initialize sensor data list
2: Collect IoT sensor readings
3: **for** each sensor record **do**
4: Generate SHA256 hash of record
5: Store hash in hash list
6: **end for**
7: **while** number of hashes greater than 1 **do**
8: Pair adjacent hashes
9: Combine and hash pairs
10: Store new hashes in updated list
11: **end while**
12: Set final hash as MerkleRoot
13: **return** MerkleRoot

B. IPFS Upload and Blockchain Anchoring Mechanism

This algorithm uploads processed sensor data to IPFS and stores the resulting content identifier along with the Merkle root on the blockchain.

1: Prepare finalized sensor dataset
2: Convert dataset into JSON format
3: Upload JSON file to IPFS via Pinata
4: Receive IPFS Content Identifier (CID)
5: Connect to blockchain smart contract
6: Call createBatch function
7: Store batchId, CID, and MerkleRoot
8: Confirm blockchain transaction
9: **return** transaction status

C. Ownership Transfer and State Update Mechanism

This algorithm ensures secure and sequential movement of products through the supply chain using an atomic smart contract function.

1: Connect wallet to blockchain
2: Retrieve current batch details
3: Verify caller is current owner
4: Check newState = currentState + 1
5: **if** condition is valid then **then**
6: Update ownership address
7: Update supply-chain state
8: emit blockchain event
9: **else**
10: Reject transaction
11: **end if**
12: Confirm transaction completion

VIII. IMPLEMENTATION AND TESTING

A. Prototype Development

The AgriChain prototype was developed using a modular approach integrating IoT data processing, decentralized storage, blockchain smart contracts, and a web-based application interface. The implementation process began

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with backend development using the Flask framework, which handles sensor data processing, hash generation, and Merkle tree construction. Sensor readings were structured into JSON format and processed to generate cryptographic hashes that ensure data integrity.

After preprocessing, datasets were uploaded to IPFS using Pinata services. The resulting Content Identifier (CID) and Merkle root were then anchored on the Ethereum Sepolia blockchain through Solidity smart contracts. Smart contracts were designed to manage batch creation, ownership tracking, and sequential supply-chain state transitions. An atomic function combining ownership transfer and state update was implemented to simplify user interaction and maintain consistency. The frontend application was developed using React and integrated with blockchain services through Ethers.js. The interface allows stakeholders to create batches, view supplychain progress, transfer ownership, and verify product details. QR-code-based verification was implemented to enable consumers to retrieve blockchain metadata and associated IPFS records for authenticity validation.

B. Performance Evaluation

The implemented prototype demonstrated stable interaction between backend services, decentralized storage, and blockchain components. Key observations include:

- Successful batch registration and blockchain anchoring
- Reliable IPFS data retrieval and verification
- Accurate enforcement of sequential ownership transitions
- Consistent Merkle root validation across datasets
- Smooth frontend interaction with blockchain transactions

The testing results confirm the feasibility of AgriChain as a decentralized agricultural supply-chain system capable of ensuring transparency, integrity, and secure traceability.

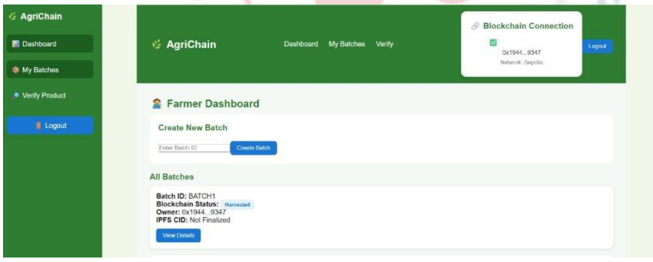

Fig. 3. Frontend part of Agrichain

IX. RESULTS AND DISCUSSION

A. Results Obtained

The implementation of AgriChain demonstrates the feasibility of integrating IoT data collection, decentralized storage, and blockchain technology into a unified agricultural supplychain framework. Experimental testing confirmed that the system successfully records and verifies supply-chain events while maintaining data integrity through cryptographic mechanisms.

The IoT data processing module consistently generated valid SHA-256 hashes, and Merkle tree construction produced stable root values for identical datasets. Any modification to sensor readings resulted in a different Merkle root, confirming the effectiveness of the integrity verification mechanism. Data uploaded to IPFS was retrieved successfully using the generated Content Identifier (CID), validating the reliability of decentralized storage.

Blockchain testing on the Ethereum Sepolia network showed successful execution of batch creation, ownership transfer, and sequential state updates. The smart contract logic effectively prevented unauthorized transitions, ensuring that supply-chain stages progressed only in the predefined order. The atomic ownership-transfer mechanism reduced transaction complexity by combining ownership and state updates into a single operation.

Frontend testing demonstrated smooth interaction with blockchain services, enabling stakeholders to track batch status and visualize supply-chain progression. QR-code-based verification allowed consumers to retrieve blockchain records and validate stored data, improving transparency and trust in product history.

B. Advantages Observed

The proposed system provides several practical advantages:

- Enhanced Transparency: All supply-chain events are recorded on blockchain, enabling traceable and tamperresistant product history.
- Data Integrity Assurance: Merkle root anchoring ensures that sensor data cannot be altered without detection.
- Efficient Storage Management: Off-chain storage through IPFS reduces blockchain costs while maintaining immutability.
- Secure Ownership Tracking: Smart contracts enforce authorized ownership transfers and sequential state progression.
- Consumer Trust: QR-based verification allows end users to independently validate product authenticity.

C. Comparison with Related Works

Compared to existing agricultural supply-chain systems, AgriChain provides a more integrated approach by combining IoT data collection, decentralized storage, and blockchainbased verification within a single framework. While many earlier solutions focus primarily on transaction recording or basic traceability, AgriChain introduces Merkle tree–based

integrity verification to securely validate large sensor datasets. Unlike systems that store data directly on blockchain, the proposed architecture uses IPFS for off-chain storage, improving scalability and reducing transaction costs. Additionally, the atomic ownership transfer and state update

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mechanism simplifies supply-chain operations compared to multi-step processes used in traditional implementations. These enhancements collectively improve transparency, data security, and operational efficiency across the agricultural supply chain.

D. Limitations and Future Scope

Some limitations were observed during implementation. Blockchain transaction delays may occur depending on network conditions, and IoT device integration requires proper calibration for accurate data collection. Future improvements may include automated anomaly detection, cold-chain monitoring enforcement, and integration of predictive analytics to enhance decision-making.

- **Zonal Field Modeling:** AgriChain divides large farms into homogeneous zones with representative sensor clusters, improving monitoring accuracy while reducing hardware costs.
- **Multi-Crop and Region-Specific Models:** AI models are adapted to different crops and regions, incorporating local soil, climate, and farming conditions for more accurate predictions.

E. Result Images of AgriChain

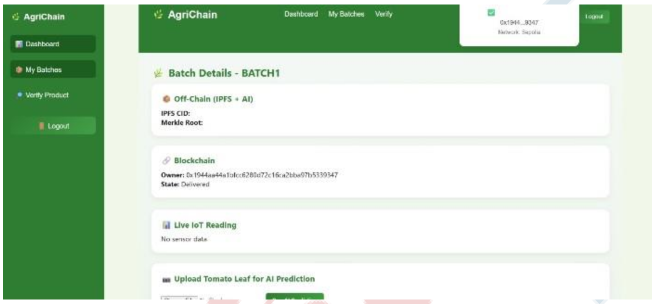

Fig. 4. Batch Details Of AgriChain

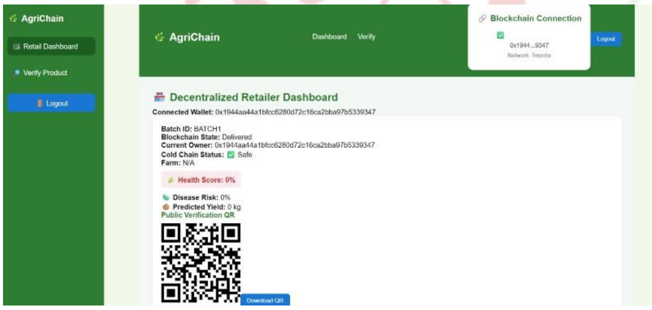

Fig. 5. QR Verification of AgriChain

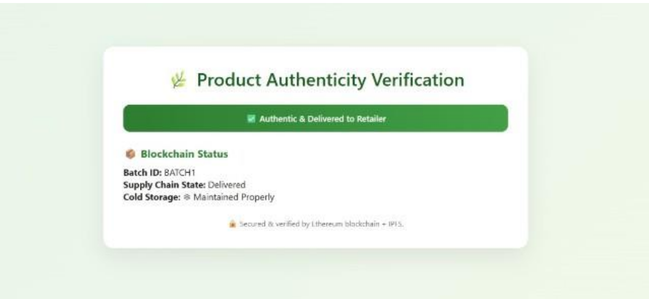

Fig. 6. Output of QR Verification

X. CONCLUSION

This paper introduces a decentralized IoT-based agricultural supply-chain solution called AgriChain that will offer improved transparency, traceability, and data integrity within the agri-ecosystem. In order to create a secure and scalable tracking infrastructure, this solution utilizes real-time environmental monitoring, cryptographic hashing, Merkle tree aggregation, decentralized storage, and blockchain smart contracts.

The hash of data collected from sensors (temperature, humidity, soil moisture, and nutrients) will be processed using SHA-256 hashes then organized into a Merkle tree so as to create an unalterable record of the sensor's data.

AgriChain's hybrid storage structure stores the entire dataset on IPFS while anchoring only the Content Identifier (CID) and Merkle root on the Ethereum blockchain, thus reducing on-chain storage costs while maintaining verifiability.

One major contribution of AgriChain is an atomic smartcontract function that allows for the combined transfer of ownership and advance in the state of the supply chain in a single transaction. This mechanism will ensure that all transitions occur in a predetermined order (e.g., from harvesting, to transportation, to storage, to delivery, or to rejection) to ensure logical accuracy and prevent any unauthorized update.

In addition, stakeholders and consumers can use the QRbased verification module to retrieve the blockchain metadata of the product so that they can verify its authenticity by comparing it with the Merkle root; therefore, establishing trust without having to rely on centralized authorities.

The prototype implementation shows how the proposed architecture has achieved an effective balance of decentralization, scalability and security by combining IoT sensing technology with blockchain-based anchoring for AgriChain (immovable traceability from farms to consumers). This solution provides a means of overcoming some of the major issues faced in today's supply chains (non-immutable data, lack of transparency), and creates a solid foundation for future improvements such as: AI-based anomaly detection; automated cold-chain enforcement; and large-scale deployment throughout distributed agricultural networks.

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