# Agriculture Supply Chain
## Blockchain-Enabled Solution

*Thesis submitted in partial fulfillment of the requirements for the degree of*

**Master of Technology**
**in**
**Computer Technology**


*Submitted by*

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This is to certify that the work embodied in this thesis entitled **"Agriculture Supply Chain: Blockchain-Enabled Solution"** has been satisfactorily completed by **Saptarshi Roy** (Registration Number 160075 of 2021 - 2022; Class Roll No. 002110504004; Examination Roll No. M6TCT24003B). It is a bonafide piece of work carried out under my supervision and guidance at Jadavpur University, Kolkata, for partial fulfilment of the requirements for the awarding of the **Master of Technology** in **Computer Technology** degree of the Department of Computer Science and Engineering, Faculty of Engineering and Technology, Jadavpur University, during the academic year 2021 - 2024.

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This is to certify that the thesis entitled **"Agriculture Supply Chain: Blockchain-Enabled Solution"** is a bonafide record of work carried out by **Saptarshi Roy** (Registration Number 160075 of 2021 - 2022; Class Roll No. 002110504004; Examination Roll No. M6TCT24003B) in partial fulfillment of the requirements for the award of the degree of **Master of Technology** in **Computer Technology** degree of the Department of Computer Science and Engineering, during the period of September 2021 to May 2024. It is understood that by this approval, the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein, but approve the thesis only for the purpose of which it has been submitted.

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# DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

I hereby declare that the thesis entitled **"Agriculture Supply Chain: Blockchain-Enabled Solution"** contains literature survey and original research work by the undersigned candidate, as a part of his degree of **Master of Technology** in **Computer Technology, Jadavpur University**. All the information have been obtained and presented in accordance with academic rules and ethical conduct.
I also declare that, as required by these rules and conduct, I have fully cited and referenced all materials and results that are not original to this work.

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*Dedicated to my unwavering pillars of support, my parents, whose love and sacrifice have fueled every chapter of my journey.*

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# *Abstract*

Computer Science and Engineering
Master of Technology in Computer Technology (MTCT)
**Agriculture Supply Chain: Blockchain-Enabled Solution**
by Saptarshi Roy

The agricultural supply chain faces significant challenges related to transparency, trust, fraud prevention, and process inefficiencies. As global trade intensifies, stakeholders—including manufacturers, importers, inspection agencies, shipping companies, and banks—require more reliable systems to ensure product authenticity, maintain quality standards, and execute secure, timely transactions. Blockchain technology, with its decentralized, transparent, and immutable nature, presents a promising solution to these issues. This work explores how blockchain can be leveraged within the agricultural supply chain, with a particular focus on the production and trade of mango pulp, to create a more efficient, accountable, and fraud-resistant network.

This work uses a methodology to examine blockchain's impact on mango pulp supply chains, highlighting specific instances where blockchain enhances transparency, reduces fraud, and ensures compliance with contract terms. Key findings indicate that blockchain not only strengthens the security and reliability of data shared among stakeholders but also enhances trust and operational efficiency through automated processes and real-time information accessibility. The study also addresses implementation challenges, including initial costs, regulatory compliance, and the need for collaboration across diverse parties to achieve effective adoption.

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CHAPTER 1

# Introduction

The agricultural supply chain is an intricate network comprising multiple stakeholders—including manufacturers, importers, inspection agencies, shipping companies, and financial institutions—working together to deliver products from farms to markets globally. With growing concerns over food security, sustainability, and transparency, agricultural supply chains are under increasing scrutiny. Despite technological advancements, these supply chains still face persistent challenges, including fraud, counterfeit products, inefficiencies in logistics, delayed payments, and lack of accountability among stakeholders. Traditional systems often rely on centralized databases or paper-based tracking, which are vulnerable to tampering, errors, and data loss, thus limiting trust and transparency within the network. Blockchain technology, with its decentralized, transparent, and immutable structure, offers a potential solution to many of these challenges, promising to transform the agricultural supply chain by enhancing efficiency, accountability, and security.

## 1.1 Background and Motivation

The agricultural sector is one of the most vital parts of the global economy, directly impacting food security and the livelihoods of millions worldwide. However, the sector suffers from a complex and often opaque supply chain, making it challenging to trace products from their origin to the end consumer. Issues such as fraudulent practices, product adulteration, and lack of reliable data affect all stakeholders. For example, counterfeit products can enter the supply chain, posing health risks to consumers and financial losses to legitimate manufacturers and importers. Additionally, the lack of transparency in quality inspections and shipping processes can lead to disputes, product delays, and unsatisfied customers.

Blockchain, known for its decentralized ledger capabilities, allows data to be

recorded in a secure, verifiable manner across all nodes in a network, ensuring that once information is entered, it cannot be altered without the consensus of all participants. This makes blockchain an ideal technology to address issues in agricultural supply chains. By offering a transparent, tamper-proof record of each transaction and event, blockchain can enhance trust, minimize fraud, and provide real-time data visibility. These capabilities align closely with the goals of agricultural stakeholders, making blockchain a promising avenue for creating a secure and accountable supply chain ecosystem.

## 1.2 Research Issues

The agricultural supply chain currently faces several significant problems, including:

• Lack of transparency: Key data points—such as product origin, quality checks, and logistics status—are often hidden or unclear, leading to a lack of trust between stakeholders.

• Fraud and counterfeiting: Without secure verification mechanisms, counterfeit or adulterated products can enter the supply chain, causing financial and reputational damage.

• Inefficient payment processes: Delays in payment processing due to dependency on intermediaries increase transaction times and costs, causing cash flow issues, especially for small-scale producers and manufacturers.

• Limited traceability: Traditional systems struggle to provide end-to-end traceability, making it challenging to verify the authenticity of agricultural products.

• Contract disputes and non-compliance: Absence of automated, en- forceable contracts often leads to disputes over terms, such as delivery time- lines and quality standards.

This research aims to address these issues by exploring blockchain as a technology that can improve the agricultural supply chain's transparency, accountability, and efficiency.

## 1.3 Objectives of the Study

The primary objectives of this research are:

1. **To assess the role of blockchain in reducing fraud and improving transparency** in agricultural supply chains, specifically in the production, quality inspection, and shipping of mango pulp.

2. **To analyze how blockchain-based smart contracts** can be used to improve compliance and accountability between manufacturers, importers, and shipping companies.

3. **To investigate blockchain's potential to streamline quality assurance** processes by enabling inspection agencies to record data in a secure, tamper-proof manner.

4. **To evaluate the impact of blockchain on payment processes** within the supply chain, particularly through automated smart contracts that facilitate faster, secure transactions.

## 1.4 Research Scope and Focus

This thesis focuses on the role of blockchain in enhancing transparency, security, and efficiency within the mango pulp supply chain, a significant segment in the agricultural trade with numerous stakeholders involved from production to international distribution. By examining how blockchain can be applied in a single agricultural product chain, this study aims to provide specific, actionable insights for broader agricultural applications. Key stakeholders analyzed in this research include:

- **Manufacturers:** responsible for sourcing and processing raw materials, and ensuring product quality.
- **Importers:** interested in verifying product authenticity, quality, and compliance with purchase contracts.
- **Inspection Agencies:** tasked with ensuring the quality and safety of products through unbiased, tamper-proof assessments.
- **Shipping Companies:** responsible for handling and transporting products while ensuring timely delivery and maintaining product integrity.
- **Banks:** engaged in financing and payment facilitation through automated contract-based releases of funds upon fulfillment of agreed terms.

## 1.5 Importance of Blockchain in the Agricultural Supply Chain

Blockchain's value proposition lies in its core characteristics:

- **Decentralization:** Blockchain operates without a single point of control, meaning that data is stored across a network of nodes. This decentralized structure prevents unauthorized alterations and ensures data redundancy.
- **Immutability:** Once recorded, data on a blockchain cannot be modified without altering the entire chain, making it highly resistant to tampering.
- **Transparency:** Blockchain allows authorized stakeholders to access real-time data, which improves visibility and accountability across the supply chain.
- **Smart Contracts:** Blockchain supports programmable contracts that can automatically execute predefined actions when conditions are met, allowing for streamlined, enforceable agreements between parties.

The agricultural supply chain benefits from these features as they directly address transparency issues, fraud prevention, efficiency, and reliability, creating a secure ecosystem for trading high-value agricultural products.

## 1.6 Significance of the Study

This research is significant as it provides a comprehensive analysis of blockchain's application in the agricultural sector, specifically the mango pulp supply chain. It contributes to existing knowledge by identifying specific ways blockchain can resolve real-world problems, such as counterfeit products, inefficient payments, and lack of accountability. Additionally, the study offers insights into the challenges of implementing blockchain, including technical requirements, regulatory considerations, and potential adoption barriers.

The outcomes of this research are expected to be valuable to agricultural stakeholders looking to modernize their supply chain operations. By demonstrating the practical benefits of blockchain, this study aims to encourage further exploration and adoption of blockchain technology within agriculture and related industries.

## 1.7 Structure of the Thesis

The remainder of this thesis is organized as follows:

- **Chapter 2: Literature Review** provides an overview of existing studies on blockchain's application in supply chain management, identifying gaps in current research and offering context for blockchain's potential in agriculture.
- **Chapter 3: Proposed Framework** leverages blockchain technology to address the challenges of transparency, accountability, and efficiency in agricultural supply chains. Specifically, this system is designed for the mango pulp supply chain and includes a blockchain network, smart contracts, and data access control mechanisms. The framework emphasizes secure, seamless interaction among manufacturers, importers, inspection agencies, shipping companies, and banks, enhancing trust and operational efficiency
- **Chapter 4: Conclusion and Future Directions** summarizes the research findings, proposes recommendations for stakeholders, and suggests areas for further research, such as expanding blockchain applications to other agricultural products and refining smart contract functionalities. .

CHAPTER 2

# Literature Review

This chapter provides a comprehensive review of existing literature on blockchain's role in enhancing agricultural supply chains, focusing on transparency, traceability, quality assurance, and payment automation. By analyzing current research on blockchain, IoT integration, smart contracts, and role-based access control, this chapter identifies key gaps that this study aims to address.

## 2.1 Overview of Blockchain Technology in Supply Chains

Blockchain is a decentralized, immutable ledger technology that allows data to be securely recorded and shared across a network of participants. Initially developed for financial transactions, blockchain's applications have extended to supply chains due to its potential to create transparency and traceability. By ensuring that each transaction is recorded in a tamper-resistant format accessible by authorized stakeholders, blockchain technology addresses long-standing issues in supply chains, such as lack of trust, fraud, and inefficiency (Nakamoto, 2008).

Several studies highlight blockchain's suitability for agricultural supply chains, where product authenticity, traceability, and transparency are paramount. According to Tian (2017), blockchain provides a unified and verifiable data platform that improves food safety, quality assurance, and fraud prevention, particularly in supply chains where product authenticity is difficult to verify. In IBM's Food Trust initiative, blockchain technology reduced the time required to trace food origins from several days to a matter of seconds, underscoring its potential for enhancing real-time traceability (IBM, 2018).

However, blockchain technology in supply chains has challenges, such as scalability, high transaction costs, and data privacy concerns. These limitations have led researchers to explore private or consortium blockchains, which allow more

efficient transaction processing and data access control (Zheng et al., 2018).

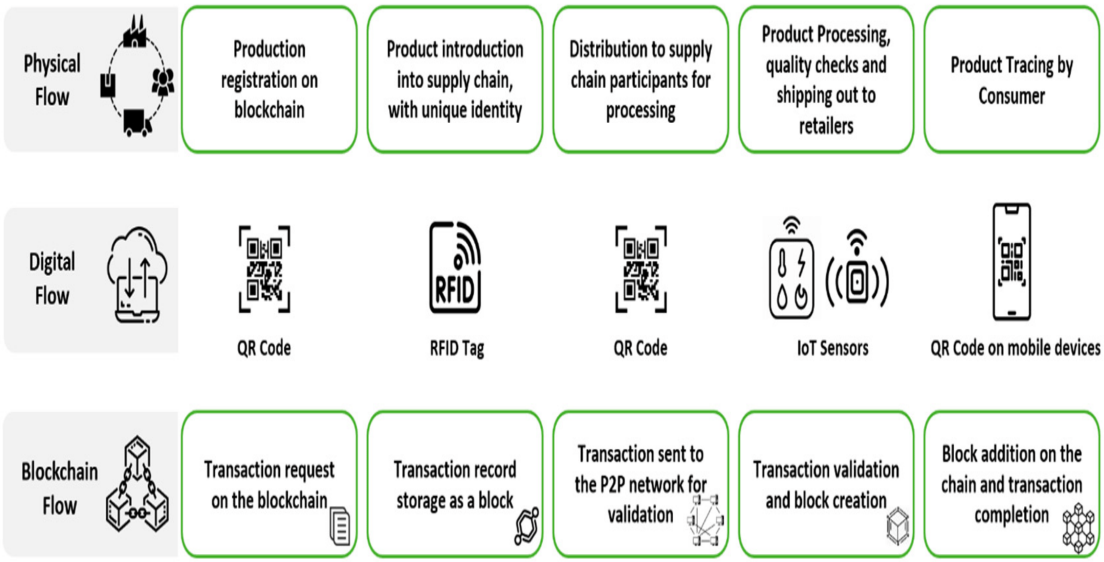



Figure 2.1: Overview of Blockchain Technology in Supply Chains [1]

## 2.2 Blockchain for Transparency and Traceability in Agriculture

Agricultural supply chains are complex, involving multiple stakeholders who need verifiable information on product origins, quality, and handling conditions. Blockchain's ability to provide a secure, immutable record has proven valuable for enhancing transparency and traceability in these supply chains. Galvez et al. (2018) found that blockchain enables comprehensive traceability in agriculture, allowing stakeholders to verify a product's journey from production to the end consumer. This transparency is crucial for products like mango pulp, where maintaining quality and ensuring authenticity are essential.

### 2.2.1 Case Studies on Blockchain in Food Supply Chains

Various case studies illustrate blockchain's role in improving traceability. For example, Walmart and IBM implemented blockchain to track the supply chain of pork in China and mangoes in the United States. This system allowed for faster, more accurate tracking of food origins, enabling rapid responses to contamination or fraud incidents (IBM, 2018). Similarly, Provenance, a UK-based company, used blockchain to track the origins of tuna, preventing illegal fishing practices and providing consumers with transparency (Provenance, 2018).

Although these implementations highlight blockchain's potential for improving traceability, they typically focus on static data recording, such as tracking batch numbers and timestamps, rather than incorporating real-time monitoring through IoT or handling multi-stakeholder compliance.

### 2.2.2 Gaps in Real-Time Traceability and Compliance

Despite the progress, blockchain in agricultural supply chains often lacks real-time data integration, which is crucial for monitoring perishable goods. Studies by Tsou (2019) and Kamble et al. (2020) note that existing blockchain solutions do not integrate IoT for continuous monitoring, which would enhance quality control and regulatory compliance. This gap highlights the need for a solution that combines blockchain and IoT, enabling stakeholders to access up-to-date information on shipment conditions and product quality.

## 2.3 Smart Contracts for Compliance and Automated Payments

Smart contracts are self-executing digital contracts with terms directly embedded in code. These contracts automatically enforce agreements, making them suitable for supply chains, where multiple stakeholders need reliable compliance and transaction processing mechanisms. Christidis and Devetsikiotis (2016) demonstrated that smart contracts could streamline supply chain processes by automating compliance checks and payment releases based on verified actions, reducing reliance on intermediaries and manual interventions.

In agricultural supply chains, smart contracts have applications in enforcing compliance with quality and delivery standards. For instance, Rejeb et al. (2020) suggest that smart contracts could automate verification processes for quality compliance and environmental conditions, such as temperature and humidity thresholds, which are critical for perishable goods. By automating payment releases upon verified delivery and quality approval, smart contracts reduce payment delays and improve cash flow for suppliers.

### 2.3.1 Case Studies on Smart Contracts in Supply Chains

Research has highlighted the use of smart contracts in automating agreements between stakeholders. A study by Zhang et al. (2019) explored the implementation of smart contracts in the pharmaceutical supply chain, where compliance with storage conditions and prompt payment upon delivery were essential. The

study showed that smart contracts minimized delays and disputes, creating a more efficient and trustworthy transaction process.

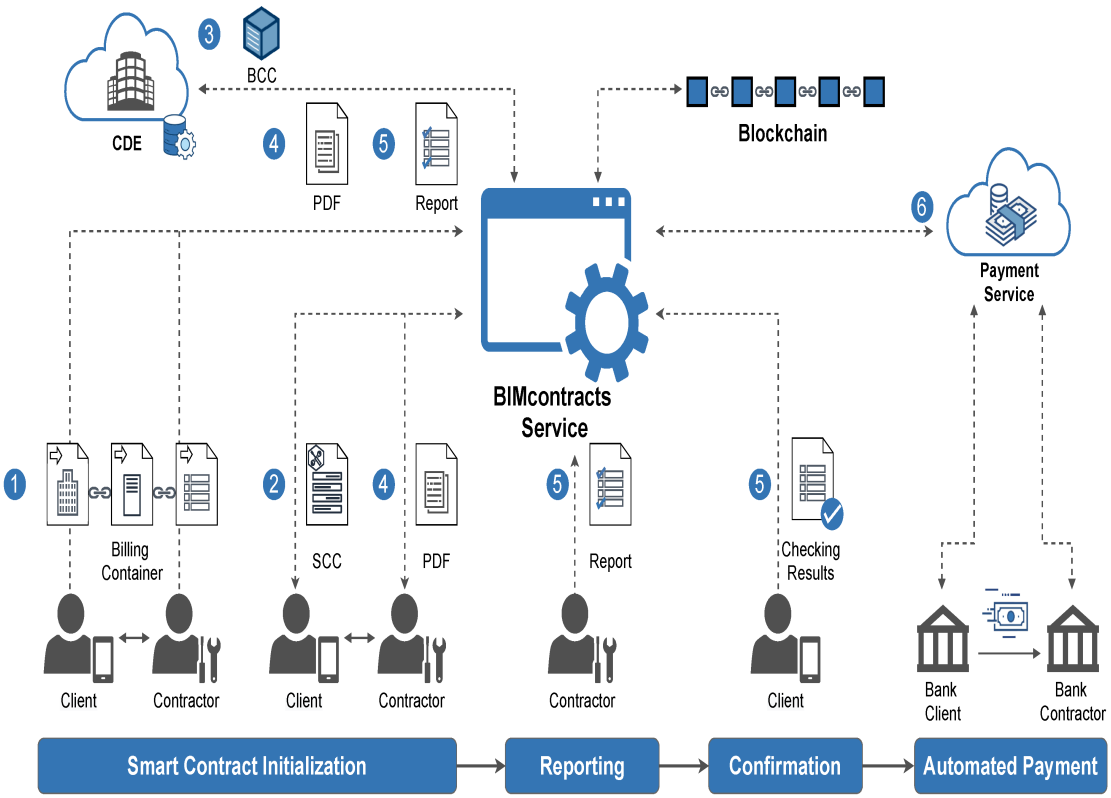



Figure 2.2: Smart Contracts for Compliance and Automated Payments[2]

However, agricultural supply chains often involve subjective assessments, such as product quality and handling practices, which are challenging to encode into smart contracts. Cong and He (2019) emphasize that while smart contracts are effective for objective conditions, encoding subjective assessments remains a barrier.

### 2.3.2 Gaps in Multi-Stakeholder Compliance and Payment Automation

Current research on smart contracts in agriculture focuses on automating transactions between two parties, typically the buyer and seller. However, agricultural supply chains often involve multiple stakeholders, including inspection agencies and banks, each with different requirements for data access and compliance verification. This gap underscores the need for smart contracts that support multi-stakeholder interactions, role-based access, and automated payment processing, ensuring that each stakeholder fulfills their role in a streamlined manner.

## 2.4 IoT Integration for Real-Time Quality Monitoring

IoT devices allow continuous monitoring of environmental conditions, providing real-time data on factors like temperature and humidity, which are crucial for perishable agricultural products. Integrating IoT with blockchain ensures that this data is securely recorded and verifiable, enabling stakeholders to monitor and verify product quality throughout the supply chain.

### 2.4.1 Benefits of IoT for Quality Assurance

IoT-enabled quality monitoring is particularly valuable for products like mango pulp, where quality degradation can occur if storage conditions are compromised. According to research by Kamble et al. (2020), IoT sensors can transmit data on environmental conditions, which can be stored on the blockchain to create a tamper-proof record of product handling. This data provides stakeholders with visibility into storage and transport conditions, ensuring that quality standards are maintained. IoT integration in supply chains has been demonstrated in industries

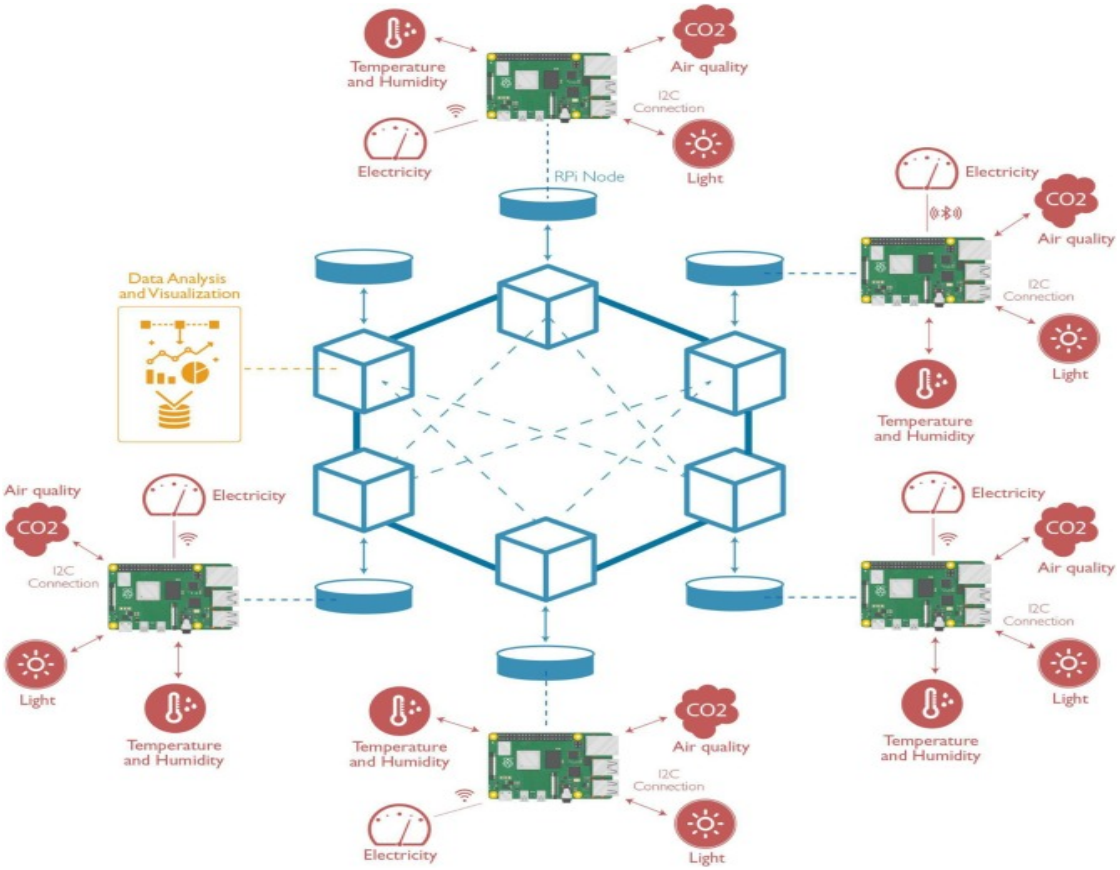



Figure 2.3: Schematic overview of the IEQ and energy monitoring system[3]

like pharmaceuticals, where products are highly sensitive to temperature changes. Studies by Tian (2016) emphasize that combining IoT with blockchain provides secure, real-time visibility into product quality, enabling faster responses to quality issues and enhancing consumer confidence.

### 2.4.2 Challenges in IoT-Blockchain Integration

Although IoT integration provides real-time data, challenges include high setup costs, data interoperability, and network latency. Kamble et al. (2020) note that smaller agricultural stakeholders may struggle to implement IoT solutions due to cost and technical complexity. Additionally, IoT devices generate large volumes of data, requiring efficient processing and storage mechanisms. Storing all IoT data on-chain is impractical due to blockchain's scalability limitations; thus, researchers recommend using off-chain storage solutions with blockchain-based verification.

## 2.5 Role-Based Access Control (RBAC) in Blockchain Systems

Role-based access control (RBAC) is essential in multi-stakeholder environments, where each participant has different access requirements. In agricultural supply chains, manufacturers, importers, inspection agencies, and financial institutions require specific data access based on their roles, such as quality data for inspection agencies and payment records for banks. By implementing RBAC, blockchain systems can ensure that each participant only accesses relevant data, protecting sensitive information while maintaining transparency.

### 2.5.1 RBAC in Permissioned Blockchains

RBAC is commonly used in permissioned blockchain networks like Hyperledger Fabric, which allows organizations to set specific access permissions for participants. Research by Ferrag et al. (2020) highlights that RBAC in blockchain networks improves data privacy, reduces data exposure, and ensures compliance with data protection regulations like GDPR. This is especially relevant in agricultural supply chains, where multiple stakeholders are involved in data entry, access, and validation.

### 2.5.2 Challenges in Implementing RBAC in Agricultural Supply Chains

Implementing RBAC in a blockchain environment requires careful management of permissions to ensure that stakeholders have appropriate access. Zheng et al. (2018) note that while permissioned blockchains support RBAC, defining and managing roles for each stakeholder can be complex in multi-party networks. Furthermore, RBAC implementations must be flexible enough to handle different access requirements, such as temporary access for auditing or inspections.

## 2.6 Gaps in Current Literature and Research Directions

The existing literature highlights the transformative potential of blockchain, IoT, and smart contracts in agricultural supply chains, yet key gaps remain:

1. **Integration of Real-Time Monitoring for Compliance**: While blockchain enhances traceability, few studies focus on integrating IoT for continuous, real-time monitoring of compliance factors, such as temperature and humidity. This gap suggests a need for IoT-enabled blockchain frameworks that provide real-time compliance verification.

2. **Multi-Stakeholder Smart Contracts for Automated Payment Processing**: Although smart contracts automate payments, research has primarily focused on two-party agreements. There is limited research on multi-stakeholder smart contracts that can automate compliance checks and payments across multiple parties, such as inspection agencies and banks.

3. **Role-Based Access Control for Sensitive Data Management**: Although RBAC is common in permissioned blockchains, there is limited research on its implementation in agricultural supply chains with complex data requirements. Future research should investigate RBAC frameworks that allow stakeholders to access only relevant data, protecting sensitive information while maintaining transparency.

4. **Scalability and Cost Efficiency in IoT-Blockchain Integration**: Integrating IoT with blockchain is resource-intensive, raising concerns about scalability and cost for agricultural applications.

CHAPTER 3

# Proposed Framework

This detailed framework is tailored for the mango pulp supply chain and is designed to tackle the specific challenges of traceability, compliance, real-time monitoring, and secure payments. This system utilizes a permissioned blockchain, smart contracts, IoT integration, and role-based access control (RBAC) to create a robust, scalable solution that enhances efficiency, transparency, and accountability for all stakeholders.

## 3.1 Framework Architecture

The proposed architecture is divided into several distinct layers and modules, each of which contributes to the overall functionality of the system. These layers work together to facilitate seamless multi-stakeholder interactions, real-time data capture, secure data storage, and automated transactions.

### 3.1.1 Key Layers of the Architecture:

1. **Permissioned Blockchain Network Layer**: The core network layer where data is recorded immutably and access is restricted to verified stakeholders. In a permissioned blockchain, transactions must be verified through a consensus algorithm, such as Practical Byzantine Fault Tolerance (PBFT). Here's how the consensus mechanism can be represented mathematically:

   Let:

   - $T_i$ = a transaction from node $i$ - $V_i(T)$ = verification result (1 if valid, 0 if invalid) by node $i$ - $N$ = total number of validating nodes - $f$ = number of possible faulty nodes (assuming a tolerance of $f < \frac{N}{3}$ in PBFT)

The transaction $T$ is verified as valid if:

$$\sum_{i=1}^{N} V_i(T) \geq (2f + 1)$$

This formula ensures that at least $2f + 1$ nodes must agree on the validity of $T$ for it to be accepted into the blockchain ledger.

2. **Smart Contract Layer**: Automates key processes, enforces compliance, and ensures fair, transparent interactions.

3. **IoT Integration Layer**: Connects real-time environmental data to the blockchain for continuous monitoring and quality assurance. Let:

   - $S(t)$ = environmental condition (e.g., temperature or humidity) at time $t$ - $S_{\text{min}}$ and $S_{\text{max}}$ = acceptable minimum and maximum thresholds for the condition $S$

   The condition for compliance during shipping is:

$$S_{\text{min}} \leq S(t) \leq S_{\text{max}}$$

   This inequality must hold for all $t$ during transportation to ensure that the product's quality is maintained. If $S(t)$ falls outside this range at any point, a penalty condition is triggered, which can be represented as an indicator function $P(t)$:

$$P(t) = \begin{cases} 1 & \text{if } S(t) < S_{\text{min}} \text{ or } S(t) > S_{\text{max}} \\ 0 & \text{otherwise} \end{cases}$$

   Total penalties $P_{\text{total}}$ for the shipment duration $T$ are then calculated as:

$$P_{\text{total}} = \int_0^T P(t)\, dt$$

   where $P_{\text{total}} > 0$ would trigger a penalty.

4. **Data Access Control Layer (RBAC)**: Manages data permissions to ensure that each stakeholder has access only to the relevant information. To model access control, let:

   - $A(u, d)$ = access function, where $u$ is the user and $d$ is the data type - $R_u$ = role of user $u$

Define access permissions for data types $d$ based on roles $R$. The access function $A(u, d)$ is defined as:

$$A(u,d) = \begin{cases} 1 & \text{if } R_u \text{ has permission to access } d \\ 0 & \text{otherwise} \end{cases}$$

This function helps ensure that each stakeholder can access only the data relevant to their role in the blockchain network.

5. **User Interface Layer**: Provides web and mobile interfaces for stakeholders to interact with the system, access real-time data, and monitor contract fulfillment. The payment release in the smart contract is based on conditions for both quality compliance and delivery confirmation.

   Let:

   - $Q_{\text{check}} = 1$ if quality check is passed, 0 otherwise - $D_{\text{confirm}} = 1$ if delivery is confirmed, 0 otherwise - $E =$ escrowed payment amount

   The payment $P_{\text{release}}$ released to the manufacturer and shipping company is given by:

   $$P_{\text{release}} = E \cdot (Q_{\text{check}} \cdot D_{\text{confirm}})$$

   If both conditions $Q_{\text{check}} = 1$ and $D_{\text{confirm}} = 1$

## 3.2 Key Components of the Framework

### 3.2.1 Permissioned Blockchain Network Layer

The blockchain network acts as the foundation of the framework, creating a secure, decentralized environment for storing and sharing data. Since the system deals with sensitive financial and quality-related information, it operates on a **permissioned blockchain** (e.g., Hyperledger Fabric) to restrict access and ensure data privacy.

· **Network Nodes**: Each stakeholder (Manufacturer, Importer, Inspection Agency, Shipping Company, Bank) is represented by a node on the blockchain, each with unique identity credentials issued by a Certification Authority (CA). Nodes validate transactions based on consensus.

· **Consensus Mechanism**: Practical Byzantine Fault Tolerance (PBFT) is employed to reach consensus efficiently, making it suitable for a private network with fewer nodes.

· **Channel Architecture**: Hyperledger Fabric supports channels, which allow private data transactions between specific participants (e.g., between the importer and manufacturer) without exposing data to the entire network. This channel architecture provides privacy while maintaining a shared, auditable record.

· **Identity and Access Management**: Every stakeholder has a unique cryptographic identity, managed through public-private key pairs, enabling secure, authenticated access to the network.

### 3.2.2 Smart Contract Layer

The smart contract layer consists of self-executing contracts coded with predefined rules and conditions, reducing the need for intermediaries, automating compliance checks, and ensuring timely transactions. Below are specific smart contracts implemented within the framework:

1. **Purchase Contract**: This contract initializes the order, specifying quantity, quality requirements, delivery date, and payment. The payment amount is held in escrow on the blockchain until conditions are fulfilled.

2. **Quality Verification Contract**: This contract allows inspection agencies to log quality check results directly on the blockchain. If quality standards are met, the contract approves the shipment; if not, corrective actions are triggered, which may include alerts to the manufacturer for remediation.

3. **Shipping Contract**: This contract monitors IoT data from sensors attached to the shipment. Parameters such as temperature and humidity are recorded on the blockchain. If conditions deviate from acceptable ranges, the contract applies penalties to the shipping company.

4. **Payment Release Contract**: Once the importer confirms that the product has been delivered in satisfactory condition and quality, this contract releases the escrowed funds to the manufacturer and the shipping company, ensuring prompt payment.

**Smart Contract Functionality**:

- **Automated Compliance Enforcement**: The smart contract validates each step based on predefined criteria, such as quality approval, shipment conditions, and delivery confirmation.

- **Real-Time Alerts and Notifications**: In case of quality or shipment deviations, the contract generates alerts to relevant stakeholders, enabling immediate action.

- **Escrow Management**: Funds are held securely within the blockchain escrow until contract terms are met, reducing payment delays and ensuring

that all stakeholders uphold their commitments.

### 3.2.3 IoT Integration Layer

This layer enables real-time monitoring of shipment conditions, crucial for the quality assurance of perishable goods like mango pulp. IoT devices equipped with sensors (temperature, humidity, GPS) continuously monitor environmental conditions, capturing data and pushing it to the blockchain network.

· **IoT Sensors**: Deployed in storage and transport vehicles, these sensors capture real-time data critical for quality assurance.

· **Data Gateways**: IoT devices send data to edge devices or gateways, which preprocess and encrypt the data before transmitting it to the blockchain to ensure privacy and prevent unauthorized access.

· **Blockchain Recording**: Data from IoT sensors, once processed by the gateway, is written to the blockchain. This approach provides a permanent, immutable record of shipping conditions, enabling quality compliance verification.

· **Event-Triggered Alerts**: When sensor data falls outside acceptable ranges, an alert is generated, notifying the relevant stakeholders and triggering corrective actions within the smart contract.

### 3.2.4 Data Access Control Layer (RBAC)

RBAC is crucial for securing data access within the multi-stakeholder environment of the supply chain. Each participant in the blockchain network is assigned specific roles, ensuring that they can access only the data necessary for their functions.

**Role Assignment:**

- **Manufacturers**: Can log production data, view shipment status, quality checks, and payment releases.
- **Importers**: Can place orders, review quality verification, and approve payments upon successful delivery.
- **Inspection Agencies**: Can log quality check results and access necessary production details for quality compliance but cannot view financial data.
- **Shipping Companies**: Can monitor real-time shipment data but have restricted access to production or financial details.
- **Banks**: Can access escrow and payment data but are restricted from viewing detailed production or quality information.

**Access Policies:** Access policies are enforced through the smart contract layer and blockchain access controls, ensuring compliance with data privacy regulations (e.g., GDPR) and secure, permissioned data sharing.

## 3.3 Workflow of the Proposed Framework

### 3.3.1 Step 1: Order Placement and Purchase Contract Initialization

1. **Importer** logs into the application, places an order for mango pulp, and initiates a **Purchase Contract** on the blockchain. This contract holds the payment amount in escrow.

2. The contract specifies key terms such as quantity, quality standards, delivery date, and payment amount.

### 3.3.2 Step 2: Production Logging and Shipment Preparation by Manufacturer

1. **Manufacturer** records production data, including details like raw material sources, production process, and quality checks, on the blockchain.

2. After production, the **Shipping Contract** is activated. The shipment is equipped with IoT sensors to monitor temperature, humidity, and location.

### 3.3.3 Step 3: Quality Verification by Inspection Agency

1. The **Inspection Agency** performs quality checks, logging the results on the blockchain through the **Quality Verification Contract**.

2. If the quality requirements are met, the shipment is approved for transport. If not, corrective actions are initiated within the contract.

### 3.3.4 Step 4: IoT-Enabled Shipment Monitoring by Shipping Company

1. **Shipping Company** collects the product and begins transport. IoT sensors monitor conditions like temperature and humidity, continuously logging data on the blockchain.

2. If environmental conditions deviate from acceptable ranges, alerts are generated, and penalties may be applied to the shipping company per the **Shipping Contract**.

### 3.3.5 Step 5: Delivery Confirmation and Payment Release

1. **Importer** receives the shipment, confirms compliance with quality and shipment conditions, and marks the order as complete.

2. The **Payment Release Contract** is triggered, releasing funds from escrow to the manufacturer and shipping company, ensuring prompt payment for all stakeholders.

## 3.4 Security and Compliance Mechanisms

**Data Security and Encryption**

- **Encryption**: All data recorded on the blockchain is encrypted to prevent unauthorized access. Sensitive information, such as financial data, is stored off-chain with only a cryptographic hash on-chain, ensuring data privacy.
- **Access Control**: RBAC policies enforce data access restrictions, ensuring that stakeholders can view only relevant information.

**Compliance and Auditing**

- **Immutable Audit Trail**: Blockchain's immutability creates a permanent audit trail, simplifying regulatory compliance and providing a reliable source of truth.
- **GDPR Compliance**: Sensitive personal data is stored off-chain with role-based permissions, ensuring compliance with GDPR and other privacy regulations.

**Dispute Resolution**

- **Automated Dispute Resolution**: Smart contracts can handle minor disputes automatically, such as small deviations in shipment conditions, by applying predefined penalties or corrective actions.
- **Manual Intervention**: In cases of larger disputes, smart contracts can notify relevant stakeholders, who can then manually intervene based on the contract's recorded data.

## 3.5 User Interface and Stakeholder Functionalities

The application's user interface (UI) includes web and mobile versions, allowing each stakeholder to monitor and manage their responsibilities. Key features include:

1. **Dashboard**: Provides a centralized view of all active orders, quality checks, payment statuses, and shipment conditions.

2. **Order Placement and Tracking**: Importers can place orders, view status updates, and track shipments in real time.

3. **Quality Control Module**: Allows inspection agencies to log quality checks, manufacturers to view inspection results, and importers to verify product quality.

4. **IoT Monitoring Panel**: Real-time data on temperature, humidity, and location, visible to shipping companies, importers, and inspection agencies.

5. **Payment Dashboard**: Displays escrow status, payment release history, and transaction records for importers, manufacturers, and banks.

## 3.6 Implementation Strategy

1. **Network Setup**: Deploy Hyperledger Fabric as the blockchain network, configuring nodes for each stakeholder and establishing channels for private transactions.

2. **Smart Contract Development**: Develop and deploy smart contracts (in Go or JavaScript for Hyperledger Fabric) for purchase orders, quality verification, shipping conditions, and payment release.

3. **IoT Integration**: Set up IoT sensors in storage and shipping facilities, with data gateways for secure transmission to the blockchain.

4. **RBAC Implementation**: Configure role-based access permissions, aligning each stakeholder's access privileges with their role in the supply chain.

5. **Frontend and Backend Development**: Build web and mobile interfaces with React and React Native for the frontend, and Node.js and Express for backend integration.

## 3.7 Algorithm: Blockchain-Enabled Agricultural Supply Chain Framework

**Input**: Order request with product details, quality standards, and delivery date

**Output**: Verified product delivery with payment released upon compliance

1. **Initialize Order and Create Purchase Contract**
   - Importer logs into the application.
   - Importer places an order with:
     - Quantity $Q$
     - Quality standards $S_{\min}, S_{\max}$
     - Delivery date $D_{\text{due}}$
     - Payment $E$ held in escrow
   - System generates a Purchase Contract on the blockchain with terms and stores payment in escrow.
2. **Production Logging by Manufacturer**
   - Manufacturer logs production details on the blockchain:
     - Production ID, raw material sources, production data, and preliminary quality checks.
   - After production is complete:
     - System activates the Shipping Contract.
     - Shipment is equipped with IoT sensors to monitor conditions.
3. **Quality Verification by Inspection Agency**
   - Inspection Agency performs quality checks on the shipment.
   - Agency logs results through the Quality Verification Contract:
     - If $S_{\min} \leq S \leq S_{\max}$, quality check passes.
     - Otherwise, corrective actions are triggered.
   - If quality check is passed:
     - Shipping Contract remains active; otherwise, the shipment is flagged.
4. **Shipment Monitoring by Shipping Company**

- Shipping Company transports the product with IoT sensors monitoring environmental conditions (temperature $T$ and humidity $H$).
- IoT data is recorded on the blockchain in real-time.
- If $T$ or $H$ deviate from allowed thresholds, an alert is generated, and penalties may apply.

5. **Delivery Confirmation and Payment Release**
   - Upon delivery, Importer verifies product compliance.
   - If conditions $Q_{\text{check}} = 1$ and $D_{\text{confirm}} = 1$ are met:
     - Payment Release Contract releases funds from escrow to the Manufacturer and Shipping Company.
   - If either condition fails:
     - Payment remains in escrow, and corrective actions may be triggered.

**End**

## 3.8 Pseudo-Code Representation

**Input**: Order($Q$, $S_{\min}$, $S_{\max}$, $D_{\text{due}}$, $E$)
**Output**: $P_{\text{release}}$ if conditions are met

```
Begin
    // Step 1: Initialize Order and Purchase Contract
    Importer places Order(Q, S_min, S_max, D_due, E)
    Create PurchaseContract on blockchain, store payment E in escrow

    // Step 2: Production Logging by Manufacturer
    Manufacturer logs ProductionData on blockchain
    Activate ShippingContract, equip shipment with IoT sensors

    // Step 3: Quality Verification
    InspectionAgency performs quality check
    if S_min <= S <= S_max then
        QualityVerification = Passed
    else
        Trigger corrective actions
    end if
```

```
    // Step 4: Shipment Monitoring
    ShippingCompany transports shipment, IoT monitors T and H
    if T or H deviate from allowed thresholds then
        Trigger alert and penalty
    end if

    // Step 5: Delivery Confirmation and Payment Release
    if Q_check == 1 and D_confirm == 1 then
        P_release = E   // Release escrow payment to Manufacturer and ShippingC
    else
        P_release = 0   // Payment remains in escrow
    end if
End
```

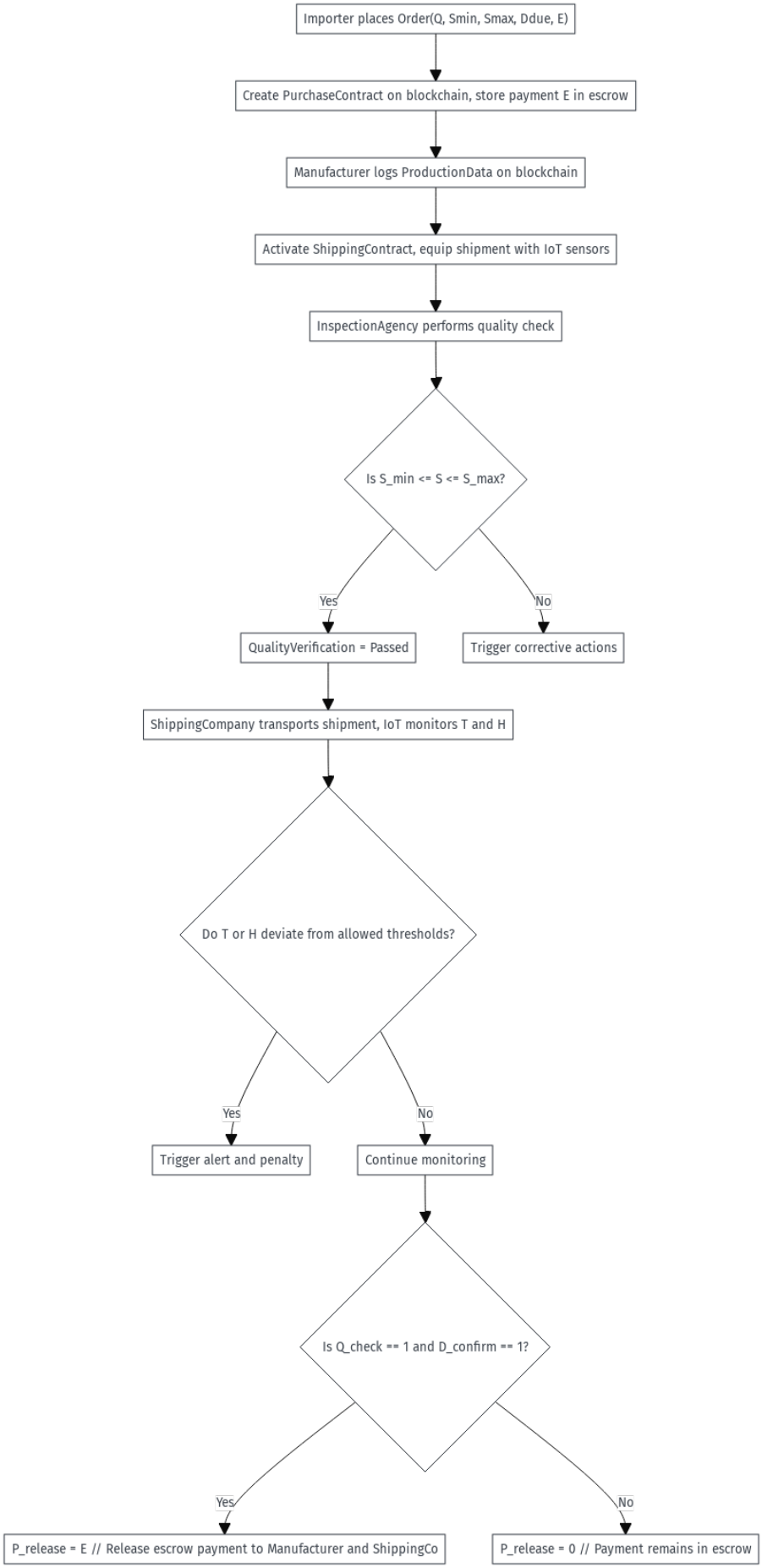



Figure 3.1: Workflow

## 3.9 Explanation of Steps

- **Order Initialization**: An importer creates an order on the blockchain, where the payment is securely held in escrow until contract conditions are met.
- **Production and Shipping**: The manufacturer logs production details and activates IoT-enabled shipment monitoring.
- **Quality Verification**: Inspection agency checks product quality. If compliant, shipment is approved; otherwise, corrective actions are initiated.
- **Real-Time Monitoring**: Shipping company monitors environmental conditions, ensuring product quality during transport. Deviations trigger penalties.
- **Delivery Confirmation**: If quality and delivery conditions are confirmed, payment is released; otherwise, payment remains in escrow.

This algorithm ensures end-to-end traceability, quality assurance, and secure payment processing in the agricultural supply chain, enhancing transparency and efficiency for all stakeholders.

CHAPTER 4

# Conclusions and Future Directions

## 4.1 Conclusion

This research proposed a blockchain-enabled framework for enhancing transparency, accountability, and operational efficiency in agricultural supply chains, specifically focusing on the mango pulp industry. By integrating blockchain technology with IoT devices, smart contracts, and role-based access control, the framework addresses critical challenges such as product traceability, quality compliance, and secure payment processing.

**Key benefits of the proposed framework include:**

- **Improved Transparency and Traceability**: Blockchain's immutable ledger provides a reliable, verifiable record of each transaction and activity, from production to delivery. Stakeholders can trace product origins and verify quality compliance, reducing fraud and enhancing trust across the supply chain.
- **Automated Compliance and Payment Processing**: Smart contracts enforce contract terms, automatically validating quality checks, shipment conditions, and payment release, minimizing disputes and delays.
- **Real-Time Quality Assurance**: IoT sensors monitor shipment conditions in real-time, ensuring product quality for perishable items like mango pulp. Deviations in conditions trigger alerts, enabling timely corrective actions.
- **Data Security and Privacy**: Role-based access control ensures that stakeholders access only relevant information, protecting sensitive data and ensuring compliance with privacy regulations.

The framework's implementation would benefit stakeholders by creating a more secure, transparent, and efficient supply chain. By applying blockchain and IoT, this solution provides a model that could be adapted to other agricultural and perishable goods supply chains, potentially transforming how sensitive products are tracked, verified, and managed.

## 4.2 Future Directions

While the proposed framework addresses several key challenges, further research and development can enhance and expand its functionality. Future directions for this research include:

1. **Scalability and Cost Efficiency**: As blockchain networks grow, they often encounter challenges with scalability and increased transaction costs. Future studies could explore optimizing consensus mechanisms, such as Proof of Authority (PoA), or using hybrid blockchain models to reduce costs and improve processing speed in agricultural applications.

2. **Enhanced IoT Integration and Predictive Analytics**: Currently, IoT sensors provide real-time data, but integrating predictive analytics could enable stakeholders to foresee potential issues, such as temperature deviations or delays, before they occur. This would help with proactive quality assurance, reducing waste and improving supply chain resilience.

3. **Interoperability with Other Supply Chain Systems**: The framework could benefit from integration with existing Enterprise Resource Planning (ERP) systems and other supply chain management tools. Developing standardized APIs and protocols for interoperability would streamline data exchange, enhancing the framework's adaptability across various industries.

4. **Incorporating Machine Learning for Quality Assessment**: Future implementations could incorporate machine learning algorithms to analyze quality data from inspection agencies and IoT sensors. This could enhance the accuracy of quality assessments, detect anomalies in real time, and further automate compliance checks.

5. **Improved User Experience and Accessibility**: As blockchain technology can be complex for new users, designing more intuitive, accessible user interfaces for all stakeholders is essential. Simplifying the interface and ensuring multilingual support could help in broader adoption, especially for small-scale farmers and suppliers with limited technical expertise.

6. **Exploring Decentralized Finance (DeFi) for Flexible Payment Options**: Integrating decentralized finance (DeFi) solutions, such as peer-to-peer lending or credit services, could offer stakeholders more flexible payment options. For example, manufacturers could access early payments or liquidity from DeFi lending protocols, which could improve cash flow, especially for small and medium-sized enterprises.

7. **Regulatory and Compliance Research**: As blockchain and IoT applications in agriculture evolve, compliance with international trade laws, food safety regulations, and data protection standards will be essential. Ongoing research on regulatory frameworks will ensure that these systems can be adopted internationally without legal complications.

8. **Extending to Other Agricultural Products and Sectors**: Although this framework focuses on mango pulp, its principles can be adapted to other high-value or perishable agricultural products, such as dairy, seafood, or organic produce. Expanding to additional agricultural sectors could reveal further benefits and optimization needs.

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