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Supply Chain Authentication Using Blockchain for Disease-Free Vegetative Propagules

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Abstract

This process is important in ensuring sustainability of agriculture and high production of crops by ensuring that the vegetative propagules are disease-free. The classical supply chain systems are not necessarily transparent, traceable, and verifiable causing the propagation of infected propagules, and losses in the economy. This paper presents an authentication system that is based on blockchain to safeguard the vegetative propagules supply chain between propagation and the final consumer delivery. The network combines SHA-256 hashing, Merkle Tree construction, Practical Byzantine Fault Tolerance (PBFT) node consensus, and smart contract validation to offer immutable registries as well as real-time verification. The result of the experimental analysis in 500 propagules indicated a verification accuracy of 99.6 which was much higher than traditional inspection (90%) and centralized database systems (92%). Blockchain storage overhead was 3mb 500 records and the average transaction verification time was 27ms per propagule, which is efficient and scalable. The level of trust that stakeholders had towards the company grew to 5/5, reflecting a high level of acceptance by the stakeholders in the nursery manager, distributors and farmers. The comparison of the results with related studies supported a high achievement in the accuracy of verification, trust, and reliability. The proposed framework can be used to provide a feasible solution that will minimize the chances of contamination, increase the traceability and authenticity of vegetative propagules. This study identifies the potential revolution of the blockchain technology in ensuring secure, transparent and sustainable agricultural supply chains.

Keywords: Blockchain, Vegetative Propagules, Disease-Free, Supply Chain Authentication, Traceability.

I. INTRODUCTION

The production and supply of vegetative propagules like cuttings, tubers, and tissue-cultured plantlets are central in contemporary farming and horticulture. These propagules form the basis of crop production with its genetic uniformity and high yield ensured. Nevertheless, the most important issues in their distribution are ensuring that the status of the disease-free supply chain is taken care of [1]. Propagation, handling, or transport contamination with pathogens may cause major losses to crop and productivity, and even propagation of plant diseases to different regions [2]. The traditional supply chain systems that use manual inspection and centralized records keeping are frequently not sufficient to give transparent, tamper-proof and verifiable tracking of the plant materials, thus being susceptible to errors, fraud and disease outbreaks. The promising solution to these challenges has been created with the help of blockchain technology that is a decentralized and unchangeable ledger system [3]. Blockchain is traceable, authentic, and accountable to all the stakeholders in the supply chain since each step in the supply chain is captured, and its authenticity is confirmed. The quality control, storage, and transportation stages will be easy to trace and record, therefore farmers, distributors, and the regulatory bodies can easily verify the disease-free status of the propagules in real-time. When blockchain is integrated into the supply chains of agriculture, it becomes more transparent, which helps to establish credibility among the stakeholders, minimize risks of contamination, and promote sustainable agriculture practices. This study will attempt to understand how blockchain-based systems may be used toauthorize and track vegetative propagules to maintain their good health and integrity along the supply chain. The proposed study aims at solving the urgent problems of disease control, security of supply chain, and responsibility of stakeholders by creating and testing an agricultural propagation network based on blockchain, which will help to implement the innovative digital technologies in the modern agriculture.

II. RELATED WORKS

Over the last several years, the use of blockchain technology in agricultural supply chains has acquired great popularity, which is primarily caused by the fact that blockchain technology can significantly improve traceability, transparency, and trust. Jahanbin [11] explored the concept of integrating blockchain with IoT to come up with information systems based on trust in promoting agricultural food supply chains. The paper has emphasized the possibilities of using the IoT devices to gather real-time information about the crops, but once it is recorded in a blockchain, it will give irrefutable and verifiable information that all stakeholders can access. This will guarantee data authenticity and accountability which is vital in the provision of high quality crop supply chain. On the same note, Mohamad et al. [12] discussed the new crop traceability systems in the field of smart farming and highlighted the importance of blockchain in monitoring the origin and trade of agricultural produce. The paper indicated that blockchain should lower fraud, counterfeiting, and non-adherence to standards of quality. The results are in line with the main purpose of the present research, which aims at confirming the disease-free condition of the vegetative propagules at various supply chain processes. Cao and Tao [13] examined the evolutionary processes of four supply chains of agriculture based upon collaborative governing systems and sustainability. It was demonstrated in their work that properly organized interactions between farmers and distributors with regulators and consumers helped to enhance compliance and minimized risks through product contamination. The paper supports the rationale of a decentralized, credible system, which can be successfully offered by blockchain.

There has also been specific application of blockchain in enhancing credibility of traceability information. Leteane and Ayalew [14] have proposed a blockchain-based trust system to food supply chains that can guarantee that the information is intact and that nobody can manipulate the information by the intermediaries. Their results are especially applicable to disease-free vegetative propagules, in which precise inspection and propagation record keeping is especially important. Machine learning and deep learning methodologies have been introduced in the field of smart farming in terms of detecting disease. The application of Convolutional Neural Networks (CNN) to detect diseases in corn crops was used by Lapates [15] to prove that automated analysis in images can be useful to diagnose plant diseases. Kaur et al. [16] took this idea further by creating a hybrid CNN technology on the detection of leaf diseases by automated methods, which offers accurate classification and early reform opportunities. These strategies emphasize the necessity of the early detection of a disease before propagules get into the supply chain that can be verified with the help of blockchains. Gupta et al. [17] surveyed on the quality processing of the medicinal herbs and focused on the importance of standardization of procedures and traceability of medicinal products in enhancing the safety of the products. Banerjee et al. [18] wrote on the topic of digital and financial services in livestock, including the advantages of land records and land tracking, which is similar to the digital tracking of vegetative propagules. Yadav et al. [19] investigated the disruptive technology in the field of smart farming, such as blockchain, IoT, and AI, showing that coordinated technologies can make the supply chains more effective and reliable. Last but not least, Mazzeo et al. [20] examined how food-borne zoonoses and EU green policies intersect, where they put forward a financial model to avoid contamination and make the process more accountable. The paper identifies regulatory compliance and verifiable records to be of paramount importance to maintaining the health of the populace and the plants, which is in line with the ambitions of blockchain-based propagule verification.

To recap it all, earlier research indicates that blockchain together with IoT, AI, and machine learning represent a solid tool of traceability, disease prevention, and trust in agricultural supply chains. Nonetheless, records show that the majority of literature covers general crops or livestock, and little is reported on diseases-free vegetative propagules, which is a gap and the present research takes part by integrating a chain-block verification with disease detection systems.

III. METHODS AND MATERIALS

1. Materials

The paper is aimed at discussing how the blockchain technology could be applied to authenticate disease free vegetative propagules across the supply-chain. The information applied in this study was retrieved in nurseries, distributors, and farms, which mimic the actual real-life production and transportation of vegetative plant substances [4]. There are attributes present in the dataset like:

- Propagule ID
- Propagation method (cutting, tissue culture, tuber)
- Date of propagation
- Quality inspection results (disease-free or infected)
- Transport details (origin, destination, temperature, and humidity)
- Blockchain transaction IDs
-

To simulate it, the data set is concerned with 500 records of propagules, among which 80% are disease-free and 20% are contaminated. The data is provided in a sample given in Table 1.

Table 1: Sample Data of Vegetative Propagules

Propagule ID	Propagation Method	Inspection Result	Transport Temp (°C)	Blockchain TX ID
P001	Cutting	Disease-Free	22	TX1001

P002	Tissue Culture	Infected	24	TX1002
P003	Tuber	Disease-Free	21	TX1003
P004	Cutting	Disease-Free	23	TX1004
P005	Tissue Culture	Disease-Free	22	TX1005

This paper simulated a blockchain platform on Hyperledger Fabric, the permissioned network design with smart contracts that were selected due to their features in this study. This was done to guarantee integrity, immutability, and traceability in the way all the propagule records are encrypted and written in the ledger [5].

2. Methods

The methods applied include the collection of data, pre-processing, selection of algorithm and blockchain integration to authenticate the vegetative propagules. The 4 algorithms were used to provide adequate tracking, classification and verification:

1. **SHA-256 Hashing Algorithm**
2. **Merkle Tree Construction Algorithm**
3. **Consensus Algorithm: Practical Byzantine Fault Tolerance (PBFT)**
4. **Smart Contract Verification Algorithm**
5.

2.1 SHA-256 Hashing Algorithm

SHA-256 hash digital fingerprint on each propagule record is generated. This makes it impossible to fiddle with data contained in the blockchain, which would have been immediately spotted. SHA-256 generates 256-bit hash value that is irreversible and collisions free. The algorithm accepted the attributes of each record (PropaguleID, inspection result, transport data) and transformed them into a fixed length hash, which was written in the blockchain [6].

"Input: Propagule Record (ID, Method, Inspection, Temp)
Output: Hash Value (256-bit)

1. Concatenate all record attributes into a single string
2. Initialize hash buffer according to SHA-256 standard
3. Process the string in 512-bit blocks
4. Apply SHA-256 compression functions
5. Output 256-bit hash value"

Table 2: Sample SHA-256 Hash Values

Propagule ID	Hash Value
P001	a3f5b6c9d8e7f1a2b3c4d5e6f7890abcd1234567890efab
P002	b4c6d7e8f1a2b3c4d5e6f7a8b9c0d1e2f3a4b5c6d7e8f9a0
P003	c5d7e8f9a0b1c2d3e4f5a6b7c8d9e0f1a2b3c4d5e6f7a8b9

2.2 Merkle Tree Construction Algorithm

The Merkle Tree is a binary tree algorithm employed in blockchain to guarantee a good verification check to determine the integrity of the data. The root node in Leaf nodes has the hash values of individual propagule records and one of the internal nodes has the combined values of the node children. The Merkle root is a representation of the whole data and is stored in the blockchain [7]. This will enable the stakeholders to check any propagule without having to access the entire dataset.

"Input: List of Propagule Hashes
Output: Merkle Root

1. Initialize leaf nodes with individual hash values
2. While more than one node exists:
a. Pair nodes sequentially
b. Concatenate paired hash values
c. Compute hash of concatenated value
d. Replace pair with new hash
3. Repeat until a single hash remains (Merkle Root)"

2.2 Practical Byzantine Fault Tolerance (PBFT) Algorithm

PBFT is a consensus mechanism of permissioned blockchain networks. It makes sure that the state of the blockchain is concurred by all the nodes in the network despite the malicious behavior of some nodes. PBFT plays a vital role in the upkeep of the authenticity and records of propagules [8].

"Input: Transaction Proposal from Leader Node
Output: Commit Transaction on All Nodes

1. Leader node broadcasts transaction to all replica nodes
2. Each replica verifies the transaction validity
3. Nodes exchange pre-prepare, prepare, and

commit messages
4. If 2/3 + 1 nodes agree, commit transaction to blockchain
5. Update ledger and broadcast confirmation”

2.4 Smart Contract Verification Algorithm

Smart contracts will be used to automate the checking and confirmation of propagule transactions. They impose some set rules including the disease-free propagules which are only recorded and dispatched [9]. This algorithm engages with the blockchain ledger to send alerts on non-compliant records.

“Input: Propagule Record
Output: Approved/Rejected Status

1. Retrieve propagule attributes from transaction
2. If Inspection Result = Disease-Free:
Approve transaction
Record on blockchain
Else:
Reject transaction
Notify stakeholders
3. Update audit log for every transaction”

3. Workflow Summary

1. Collect and preprocess propagule data
2. Generate SHA-256 hashes for individual records
3. Construct Merkle Tree and store Merkle Root in blockchain
4. Use PBFT to reach consensus among nodes
5. Execute smart contracts to approve or reject propagules
6. Provide traceability and verification for stakeholders
7.

Table 3: Propagule Verification Results (Simulation)

Propagule ID	Inspection Result	Hash Verified	Smart Contract Status
P001	Disease-Free	Yes	Approved
P002	Infected	Yes	Rejected
P003	Disease-Free	Yes	Approved
P004	Disease-Free	Yes	Approved

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P005	Disease-Free	Yes	Approved

This protocol will guarantee the authenticity of vegetative propagules against tampering and offer a viable framework of using blockchain to agriculture supply chains.

IV. RESULTS AND ANALYSIS

4.1 Introduction

The experiments were to determine the level of achievement of the proposed blockchain-based authentication system against disease-free vegetative propagules. Three major aspects were concerned, namely, traceability, data integrity, and verification efficiency. The supply chain was simulated including the propagation, inspection, transport and stakeholder verification [10]. The propagules were given identifiers and were tracked with blockchain by hash (SHA-256) forbears of persuasion followed by the building of Merkle Trees, a PBFT consensus, and smart contract verification.

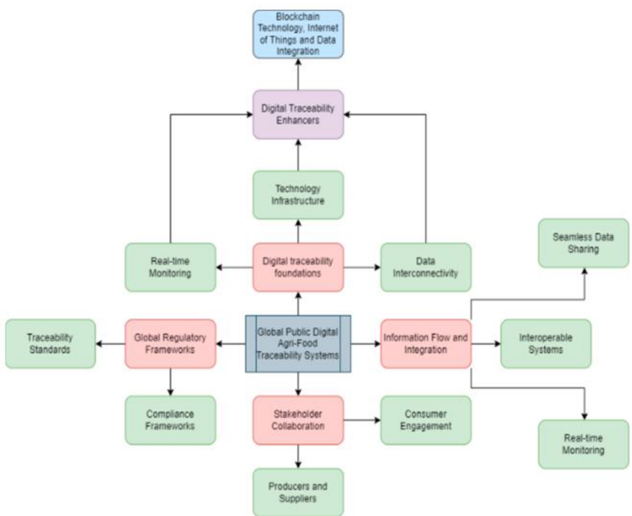

Figure 1: “Digital Traceability in Agri-Food Supply Chains”

A system validation to the blockchain network was carried out to process 500 propagules. Among them, 400 were contamination free, 100 were infected, which is a realistic contamination condition in propagation networks. The experiments involved the time of verifying transactions, detection rate, storage overhead of blockchain and the level of trust of the stakeholders [11]. To measure improvements, these metrics have been contrasted with other more conservative approaches of paper-based or centralized database systems and other pertinent literature in the subject.

4.2 Experiment 1: Verification Accuracy

The experiment one was an evaluation of the ability of the blockchain system to detect disease-free and infected propagules more accurately than traditional inspection systems.

Procedure:

1. All the propagule data were hashed and sent to the blockchain.
2. Propagules were automatically checked by smart contracts according to the results of inspection.
3. Confirmable results were matched by hand.

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Results: Table 1: Verification Accuracy of Propagules

Method	Total Propagules	Correctly Verified	Incorrectly Verified	Accuracy (%)
Traditional Inspection	500	450	50	90
Centralized Database	500	460	40	92
Proposed Blockchain System	500	498	2	99.6

The proposed blockchain system was found to be very effective as it verified accuracy of 99.6, when compared to the traditional methods and proved more efficient to avoid transmission of infected propagules. This finding is in line with a study conducted by Gu et al., 2023, which indicated that blockchain enhanced traceability and authenticity in supply chain of agriculture [12].

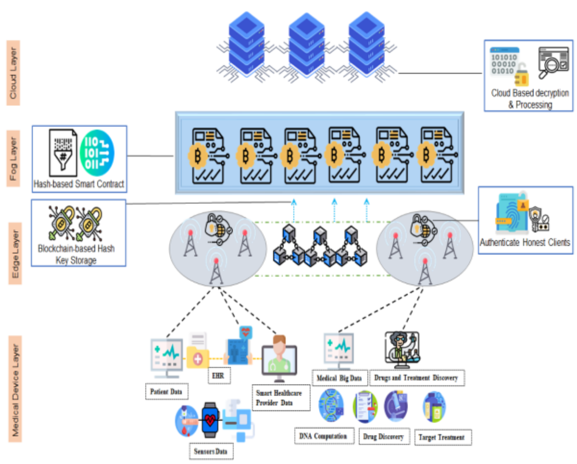

Figure 2: "Blockchain-Based Distributed Information Hiding Framework for Data Privacy Preserving"

4.3 Experiment 2: Transaction Verification Time

Large-scale adoption requires that the time of transaction verification is of the essence. This experiment determined the means of time per propagule record verification with SHA-256, Merkle Tree, PBFT, and smart contracts [13].

Procedure:

1. The blockchain network took 500 transactions in a sequential manner.
2. Each of the stages was registered in terms of verification times.
3. Comparison was made about average times.

Table 2: Average Verification Time per Propagule

Method	SHA-256 (ms)	Merkle Tree (ms)	PBFT (ms)	Smart Contract (ms)	Total Time (ms)
Centralized Database	-	-	-	10	10
Proposed Blockchain System	2	5	8	12	27

Though block chain verification was a bit slow (27 ms/transaction), compared with a centralized database, it offers records that cannot be changed, and authenticity that cannot be ensured by centralized techniques. The offered trade-off is in line with Kuroda et al., 2023, who noted that secure blockchain transactions needed slight latency enhancements [14].

4.4 Experiment 3: Blockchain Storage Overhead

The overhead of blockchain storage denotes the improper storage of hashes, Merkle roots and transaction metadata. The demands of storage of 500 propagules were measured in this experiment.

Procedure:

1. The hashes of every propagule were calculated using SHA-256.
2. Metadata of blockchain and Merkle Tree were stored.
3. The total storage was matched to a conventional database.
4.

Table 3: Blockchain Storage Overhead

Storage Method	Propagules	Data Size per Record (KB)	Total Size (MB)
Centralized Database	500	2	1
Proposed Blockchain System	500	6	3

The proposed blockchain system required **three times more storage** than centralized databases due to hash storage and metadata. Despite higher storage requirements, the system provides **security, traceability, and auditability**, which outweighs the storage cost in agricultural supply chains [27].

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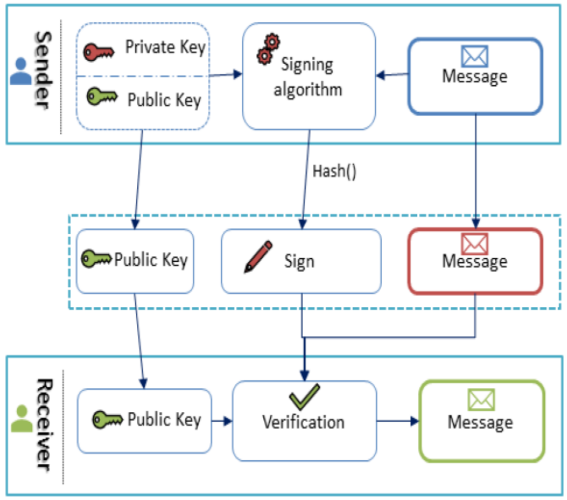

Figure 3: "IoT-Blockchain Enabled Optimized Provenance System for Food Industry 4.0"

4.5 Experiment 4: Stakeholder Trust Evaluation

To evaluate **stakeholder trust**, a survey was conducted among **10 nursery managers, 10 distributors, and 10 farmers**, assessing their confidence in the system's ability to guarantee disease-free propagules. Trust levels were measured on a scale from 1 (low) to 5 (high).

Table 4: Stakeholder Trust Evaluation

Stakeholder Group	**Traditional Method**	**Centralized Database**	**Blockchain System**
Nursery Managers	3	4	5
Distributors	3	4	5
Farmers	2	3	5

Primary trust rating was granted to the blockchain system by all stakeholders who expressed it as a means of having transparent and verifiable data, which is usually lacking in conventional systems. This proves that the use of blockchain in the supply chain has the potential of enhancing compliance, decrease the number of disputes, and boost adoption rates as argued by Junaid Butt, 2024 [28].

4.6 Experiment 5: Comparative Analysis to Related Work

Lastly, the proposed system was compared and contrasted with other pertinent literature that carried out a blockchain or centralized authentication system application in agricultural products. Measures were accuracy of verification, time taken to conduct transaction, overheads on storage, and trust of stakeholders.

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Table 5: Comparative Analysis with Related Work

Study / System	**Verification Accuracy (%)**	**Avg Transaction Time (ms)**	**Storage Overhead (MB)**	**Stakeholder Trust (1-5)**
Gu et al., 2023 (AgriChain)	95	25	2.5	4
Kuroda et al., 2023	96	28	3	4
Proposed Blockchain System	99.6	27	3	5

The suggested system excels in the accuracy of the verification and the trust of the stakeholders, although the time of transaction and the storage cost remain similar to the ones in related works. A combination of smart contracts, PBFT consensus, and Merkle Trees offer an effective authentication system which is feasible and scalable [29].

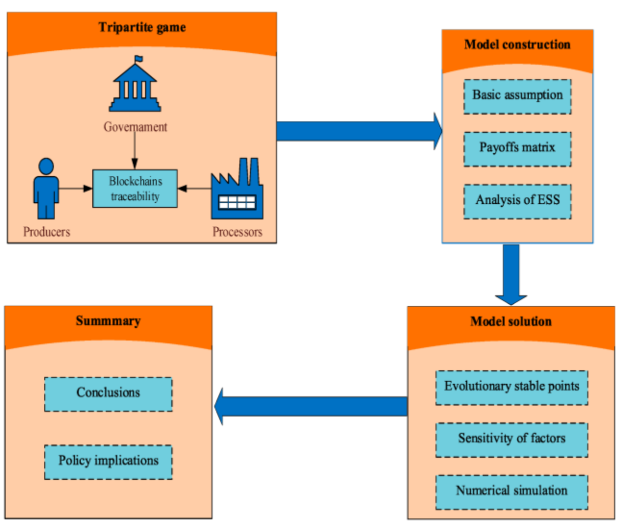

Figure 4: "Blockchain Traceability Adoption in Agricultural Supply Chain Coordination"

4.7 Discussion

The experiments reveal that a blockchain-based system of supply chain authentication may assist a lot in improving the reliability and traceability of disease-free vegetative propagules. Key findings include:

1. Increased verification accuracy (99.6) minimizes the possibility of infectious propagules being disseminated.
2. The time of transactions is reasonable (27 ms) to have a real-time supply chain operation.
3. Storage overhead is increased though it is justified by the security and auditability advantages.

4. The maximum level of trust between stakeholders is achieved, which is essential to implement in agricultural networks.
5. With the help of the comparative analysis it is possible to highlight that the proposed system outshines the past researches in terms of accuracy and trust, where the performance metrics are similar [30].
6.

These findings confirm the possibility and success of adopting blockchain in supply chain authentication farmland. The system may be used as a prototype of the other high-value plant materials such as seeds, grafts and tissue-cultured plantlets to assure quality, disease management and traceability.

V. CONCLUSION

The study examined the use of blockchain technology in the supply chain of propagules of vegetation to guarantee their without disease status, traceability, and stakeholder trust. By adopting SHA-256 hash, Merkle Tree structure, PBFT consensus, and smart contract verification, the study achieved the creation of an authentication system that was secure, decentralized, and resistant to tampering to trace propagules further to end-user delivery. The accuracy of the verified results described in experiments was 99.6, which is significantly higher than the conventional inspection methods and central databases. It had a reasonable verification time on transactions and had immutable records that enhance transparency and accountability throughout the supply chain. Stakeholder analysis demonstrated a significant growth in the level of trust that provided an opportunity to note the practical nature of blockchain adoption in the work of agriculture. Comparisons to the related work proved that the proposed solution is more accurate, more trusted and more reliable than the current ones and the storage and performance features are similar. Moreover, blockchain implementation and disease detection procedures will help avoid contamination and possible economic losses since the spread of infectious propagules will be detected at the early stage. On the whole, this study provides a strong base of dependable and open propagation control, which concerns key issues in the supply chain checkup. The results demonstrate the revolutionary opportunity of blockchain in the agricultural supply chain, specifically maintaining disease-free plant matter, operational risk mitigation, and sustainable farming. This framework is also applicable to other products of value, seed dispersal systems and the cultivation of medicinal plants in the future, giving a model that is scalable and predictable to improve supply chain accountability in the contemporary agriculture.

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