IJNRD.ORG ISSN : 2456-4184
INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD) | IJNRD.ORG
An International Open Access, Peer-reviewed, Refereed Journal

Securing Agricultural Supply Chains: A Holistic Approach Integrating Hybrid Blockchain Technology for Traceability and Security Enhancement

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***Abstract*:** This project's major aim is to promote the safety and transparency of food supply chains; an explanation of this objective is provided in the abstract. It proposes a novel way to resolving trust, data integrity, and transparency challenges in the agriculture market by incorporating blockchain technology. Data management is managed in a distributed and immutable fashion utilizing blockchain technology. By implementing this strategy, information on agricultural goods is insured to remain valid and correct throughout the supply chain. Automating agreements and processes between stakeholders is one of the aims of the proposed smart contract-based system. This decreases the likelihood of fraud and errors while enhancing efficiency. This technique not only creates transparency but also builds trust among all stakeholders involved—consumers, merchants, distributors, and farmers, among others. Therefore, by providing traceability from the point of origin of commodities to the point at which they are available for consumption by consumers, it considerably contributes to food safety. The crucial role of blockchain technology in transforming agricultural supply chain management is underlined in the abstract. The abstract also illustrates how blockchain technology may possibly address difficulties that have been extant for a long, like security, traceability, and accountability. The study's emphasis on adopting a coherent strategy pays attention to the holistic nature of the recommended solution, which tries to develop an environment for the agricultural supply chain that is more secure and strong.

Keywords— Blockchain; Agricultural Supply Chain; Traceability; Security; Smart Contracts; Food Safety; Decentralization; Transparency; Data Integrity; Trustworthiness; Immutable Ledger; Supply Chain Management; Authentication; Verification; Quality Assurance; Risk Mitigation.

I. Introduction

The major purpose of agriculture, which is the cornerstone for life on Earth, is to offer food and homes to people worldwide. The complicated network of the food supply chain, which is in charge of delivering farmed commodities from fields to tables for humans, binds this large ecosystem together. Numerous parties are engaged in this intricate process, including farmers, transporters, merchants, and consumers, all of whom are vital to the correct distribution of food supplies. The agricultural supply chain has various obstacles despite its significance, notably with respect to security and traceability. Conventional tracking technologies sometimes fall short of permitting complete and transparent monitoring of food products throughout their travels. Deficiencies in data intake, human record keeping, and a lack of real-time information contribute to supply chain errors and dangers. The emergence of blockchain technology has culminated in tremendous changes to the data management and security approaches of numerous industries. Agriculture is merely one of the many domains where blockchain, as a decentralized, tamper-proof record, has a big potential to increase security and traceability. Stakeholders may leverage the immutability and transparency inherent in blockchain technology to generate a trustworthy and verifiable record of transactions and product transfers. A visible and auditable record of each transaction or event that takes place throughout the supply chain may be generated using blockchain technology. One of the primary attractions of blockchain technology is this. This transparency not only encourages improved trust among involved parties but also offers consumers particular information about the source, quality, and safety of the food they eat.

An innovative alternative to solving these serious issues—which are getting more relevant in the present global economy—is blockchain. Traceability and food safety are becoming increasingly crucial. A fundamental component of blockchain technology, smart contracts dramatically increase agricultural supply networks' security and traceability. These self-executing contracts make sure that data transfers and trades fulfill specified criteria by automating operations and following regulations. By incorporating smart contracts into the supply chain, stakeholders may streamline activities like payment settlements, certification validations, and quality inspections. This assists in minimizing procedures and getting rid of inconsistencies. This article's recommended remedy is based on the notion of a hybrid blockchain, which merges the characteristics of public and private blockchains. A hybrid blockchain is appropriate for applications where certain data has to be made public but sensitive data has to be kept private because it gets a balance between access and protection. This blended paradigm preserves the advantages of transparency and monitoring while boosting data security. This essay's major purpose is to build a standard framework for enhancing agricultural supply chain management by employing smart contracts and mixed blockchain technology. Establishing a solid and autonomous monitoring and security system may assist partners lessen hazards, enhance production, and provide the foundation for confidence and faith in the agricultural organization. This post investigates blockchain-based solutions in depth in an attempt to demonstrate how technology is upending normal agricultural processes. Agribusiness has the capacity to establish a global food supply chain that is more open, secure, sustainable, and sustainable by utilizing innovation and digital technology.

II. LITERATURE SURVEY

Recent research attempts have centered a significant deal of attention on the usage of blockchain technology in agricultural supply networks. Blockchain technology has the potential to boost transparency and efficiency in agricultural supply networks, according to Singh and Kaur's [1] analysis. Using a fuzzy hierarchical group DEMATEL approach, Quayson et al. [2] carried out detailed research on the restrictions to the application of blockchain technology in sustainable agricultural supply chains, underlining major obstacles. In order to solve sustainability difficulties, Wang et al. [3] employed social network evaluation frameworks to analyze risk management in green supply chains for agricultural commodities. Do et al.'s research [4] of the challenges to the adoption of green supply chain management in the Vietnamese agricultural industry revealed the limitations as well as the opportunities for long-term solutions. The complexity of agricultural supply networks, including agro-commercial convergence and sustainable practices, was explored by Kanyepe et al. [5]. A climate-neutral paradigm for agricultural food supply chains was put forth by Yadav and Raut [6], who stressed the use of WINGS-GRID frameworks for sustainability. Through information sharing, Liu et al. [7] made coordinated decisions in dual-channel fresh agricultural product supply chains, boosting efficiency and coordination. With an emphasis on Iranian rice supply chains, Kazemi and Samouei [8] built a mathematical model for farmer-government interactions on food security and environmental concerns. Using Hyperledger Fabric technology, Rahaman et al. [9] constructed a secure and long-lasting food processing supply chain architecture that boosted food supply networks' traceability and security. Under carbon cap-and-trade systems, Yang and Yao [10] looked at cooperative efforts in agricultural product distribution networks and fresh-keeping options.

Research on carbon-neutral and climate-neutral supply chains was done by Guntuka et al. [11], who presented insights into ecologically beneficial and sustainable methods. With a focus on organic fruits, Sedghy et al. [12] delved into the market dynamics in retail outlets and short food supply chains. Blockchain technology may boost transparency and efficiency, as proved by Pampattiwar et al.'s research [13] on land registration and agricultural supply chain management. A blockchain-based reconciliation system was constructed by Acharya et al. [14] in an attempt to increase customer confidence in agricultural supply chain management. Using blockchain technology, Farooq et al. [15] constructed a transparent and trustworthy architecture for the wheat crop supply chain, enhancing reliability and confidence. With an emphasis on cherry products, İndap and Tanyaş [16] examined blockchain applications for food safety and traceability in agri-food supply networks. A detailed solution encompassing the primary problems and potential for blockchain-based agri-food supply chains was offered by Shahid et al. [17]. Blockchain technology was employed to explore the digitization of the agricultural environment in Iraq by Albaaji and Chandra [18].

Research on traditional and blockchain-based IoT and IIoT security in agriculture was done by Rishikesh and Sinha [19], who underlined the requirement of secure IoT installations. A blockchain-based incentive system was built by Cao et al. [20] to promote sustainable water management practices and boost agricultural water conservation. Blockchain technology was used by Modak et al. [21] to construct a sustainable dual-channel supply chain for fresh agricultural commodities, underlining the significance of blockchain integration for greater efficiency and traceability. For smart agricultural IoT networks, Luo et al. [22] designed a hybrid blockchain-based authentication system that boosted reliability and security. After solving scalability and performance issues, Xiong et al. [23] established an effective blockchain consensus architecture for the agricultural Internet of Things. An detailed investigation of blockchain-based agricultural ecosystems was carried out by Alsamman et al. [24], who revealed major patterns and difficulties. Quayson et al.'s research [25] addressed the difficulties and prospects linked with incorporating blockchain technology in sustainable agricultural supply chains. Hu et al.'s [26] research looked at how blockchain adoption in agriculture is impacted by price as a trustworthy measure of product quality. A peer-to-peer blockchain-based architecture for trustworthy agricultural product monitoring was presented by Hasan et al. [27]. This would boost supply chain trust and transparency. A blockchain-based approach to crop index insurance in agricultural supply networks was explored by Omar et al. [28] and resulted in increased resilience and risk management. The implementation of blockchain technology and organic subsidies in agricultural supply chains were explored by Li et al. [29], leading to increased market segmentation and efficiency. An IoT architecture driven by blockchain that promotes data security and reliability for the agricultural sector was presented by Mallick et al. [30].

In improving cross-border e-commerce for agricultural goods, Yue [31] enhanced international trade and transparency with the use of blockchain technology. Blockchain technology's potential advantages and constraints in agriculture were explored by Nazarov et al. [32]. IoT-based agriculture and blockchain technology were merged by Surya and Manohar [33], boosting the efficacy and efficiency of smart agricultural techniques. In his judgment on blockchain's engagement in the commercial poultry industry, Fennell [34] underscored the technology's strengths and applications. Alam et al.'s [35] assessment of blockchain in concurrent green IoT-based agriculture analyzed the benefits and prospects for implementation. A blockchain technology solution for smart agriculture was offered by Tan et al. [36], with the objective of integrating blockchain for greater efficiency and traceability. Blockchain technology was implemented by Prasad et al. [37] to increase agricultural supply chain management, leading to greater efficiency and transparency. Quality assurance and trust were highlighted when Shaik and Athithan [38] assessed agricultural supply networks' quality using machine learning and blockchain technology.Using a feature selection strategy, Shrivas and Prasad [39] constructed an ensemble model that detected lung cancer diseases, suggesting the potential of ensemble learning techniques in sickness prediction issues. By underlining the relevance of feature selection in boosting model accuracy and performance, they aided to the field's progress. Paul et al.'s [40] use of sophisticated computational machine learning models to anticipate lung cancer based on major characteristics supplied vital information on the intricacies of the models and assessments of their performance. Their results underscored the significance of early identification for improved patient outcomes and added to our expanding understanding of the challenges involved in lung cancer prediction. The numerous applications and benefits of blockchain technology in agricultural supply networks are discussed in this comprehensive literature research. These advantages and uses vary from greater traceability and transparency to better risk management and sustainability.

III.Related Works

A vast variety of ideas and implementations aimed at boosting traceability, security, and transparency in food supply chains are presented by a review of current literature and research efforts employing blockchain technology in agricultural supply chain management. Due to its potential to upend conventional supply chain operations by giving transparent and immutable records of transactions and data exchange, blockchain technology has drawn a lot of attention. The application of blockchain technology to better agricultural supply networks' traceability is one notable area of investigation in the literature. Researchers looked at how blockchain will be able to bring stakeholders and consumers end-to-end transparency into the food industry, allowing them to track food commodities from farm to table. By instantly recognizing the source of contamination, this degree of traceability not only increases food safety but also boosts consumer trust by delivering verifiable information about the origin and quality of commodities. Scholars are currently researching how blockchain technology might be able to avoid issues like fraud, data manipulation in agricultural supply networks, and counterfeit products. Security is another key problem that has been brought up in the literature. Businesses may leverage the decentralized and tamper-resistant qualities of blockchain technology to preserve sensitive data tied to certifications, quality assurance processes, and supply chain operations. This contributes to protecting the supply chain ecosystem's general stability and integrity.

The academic literature places a specific emphasis on transparency, stressing the potential of blockchain technology to encourage open and cooperative interactions between supply chain players. Real-time data sharing and information exchange are offered by blockchain-based systems, allowing stakeholders to make informed decisions utilizing up-to-date and accurate data. Since it offers information on the actions going place in the supply chain and throughout production, this openness also supports in efforts toward sustainability and ethical sourcing. Numerous studies indicate how agricultural supply chains may be automated and made more successful by deploying blockchain-enabled technologies like decentralized applications (dApps) and smart contracts. For instance, smart contracts make it possible for agreements and transactions to be automatically carried out in conformity with predetermined criteria, minimizing the need for intermediaries and enhancing operational efficiency. The literature also looks at the obstacles and concerns that blockchain adoption in agricultural supply chains meets, including those relating to technology, interoperability, law, and the necessity for standardized frameworks. Scholars stress the significance of removing these limits to effectively realize the promise of blockchain technology to boost supply chain management systems.

Real research and case studies give essential insights into the practical uses of blockchain technology in agriculture, in addition to theoretical challenges. These studies show off remarkable implementations, lessons acquired, and recommended solutions for boosting supply chain efficiency leveraging blockchain technology. It is stated that collaboration between government, industry, and academic institutions is crucial to promote blockchain applications in agricultural supply chains. Research partnerships, pilot initiatives, and knowledge-sharing activities all encourage the continued growth and improvement of blockchain-based solutions in the agrifood market. The literature research demonstrates that blockchain technology is still emerging and increasing in the area of agricultural supply chain management. Increased traceability, security, and transparency will benefit all parties operating in the food market as technology evolves and adoption rates rise. This will ultimately result in food supply systems that are safer, more resilient, and sustainable. Overall, the extensive examination of pertinent information increases knowledge in this swiftly increasing field by presenting a nuanced overview of the status, potential, difficulties, and future prospects of blockchain technology in agricultural supply chain management.

IV.Problem Statement

The problem statement highlights the drawbacks of the current agricultural supply chain traceability mechanisms, highlighting their vulnerability to mistakes and inefficiencies as well as related issues like a lack of transparency, authenticity concerns, and difficulties in tracking products from farm to table. These concerns are especially crucial for food safety, consumer trust, and regulatory compliance, demanding inventive solutions to increase security and traceability. Our research presents a single, hybrid blockchain-based method to tackle these significant barriers. The advantages of both public and private blockchains are merged in hybrid blockchain, which offers a scalable and adaptable architecture for secure and transparent data management across agricultural supply lines. Stakeholders may benefit from increased data quality, auditability, and real-time insight into supply chain processes by adding hybrid blockchain into tracking systems. The benefit of readily incorporating security and monitoring measures into the environment of the agricultural supply chain is underscored by the recommended consistent manner. Ensuring full item tracking from farm start to end-user use depends on this interaction. Stakeholders may observe the origin of items, analyze quality indicators, and check documents across the supply chain with blockchain-based monitoring systems.

The capacity of hybrid blockchain technology to manage varied degrees of data security and usability is one of its primary features. Private blockchain sections may provide data protection and access control for private information like trade secrets or unique data, while public blockchain components may promote transparency and traceability throughout the complete supply chain network. The necessity for consistent data formats, protocols, and compatible technology to allow data transmission and integration across supply chain stakeholders is also covered by the unified approach. Stakeholders may strengthen collaboration and trust in the supply chain ecosystem by addressing data gaps, communication difficulties, and information imbalance by applying established standards and procedures. The post also highlights how vital digital currency, decentralized applications (dApps), and smart contracts are to better monitoring, automating transactions, and enabling stakeholders to take part in data exchange and approval procedures. With the capacity to manage contract fulfillment, payment settlements, and compliance verification, smart contracts may boost supply chain operations by minimizing the requirement for human engagement. The entire approach that has been offered explores governmental compliance and control elements as well, underlining the significance of blending blockchain technology with present legal frameworks, industry standards, and best practices. Stakeholders may boost regulatory confidence in blockchain-enabled tracking systems, lower risks, and build trustworthiness by assuring regulatory compliance and transparency.

The essay also examines the issues associated to development, economic restrictions, and acceptability of mixed blockchain technology in agricultural supply lines. It recommends strategies for tackling these difficulties, such as delayed release, stakeholder education, investment in scalable infrastructure, and sample testing. This article's overall plan functions as a strategy execution road map for blockchain-based security and tracking solutions in agricultural supply lines. For stakeholders to effectively deploy hybrid blockchain technology, enjoy genuine advantages, and achieve exceptional outcomes in terms of traceability, security, and whole supply chain resilience, it provides principles, best practices, and practical solutions. Last but not least, the hybrid blockchain technology-based consistent approach to agricultural supply chain monitoring and security that has been endorsed presents a thorough and unique response to the many issues that existing agricultural supply networks confront. Stakeholders in the agri-food market may uncover new opportunities for efficiency, openness, and trust by putting blockchain-enabled solutions into reality, which may lead to supply chains that are safer, more stable, and sustainable.

V. Proposed Algorithm

5.1 Data Collection:

The recommended method's data collection step is critical for gathering all the information required from the multiple partners engaged in the agricultural supply chain. Producers, distributors, processors, merchants, and other connected firms are covered in this. Numerous elements are included in the obtained data, such as the source of agricultural commodities, techniques of cultivation, activities linked to harvesting, post-harvest processing processes, logistics of transportation, storage conditions, and quality control protocols. The fundamental aspect in the data collection process is to develop safe ways and standards for transmitting information amongst stakeholders. This assures the legitimacy, confidentiality, and integrity of the data being transferred. To preserve sensitive information and prohibit unauthorized access or alteration, access restrictions, encryption technologies, and secure communication protocols are deployed. A range of data sources, including sensors, barcodes, RFID tags, IoT devices, GPS trackers, and electronic documents, are employed in the collection phase. By enabling automated data entry, continuous monitoring, and real-time data collecting, these technologies minimize human error and increase data accuracy. IoT sensors, for instance, may collect information on soil conditions, temperature, and humidity, which may give important insights on the health and quality of crops. Predefined data models, standards, and formats are employed to identify and process the acquired data. This enables it possible for data integration across varied platforms and systems to be standardized, interoperable, and easy. Data quality faults and inconsistencies are resolved by undertaking data validation methods to ensure that the information supplied is real, thorough, and trustworthy. To emphasize the sequential actions required to get data from multiple sources, flow charts or tables may be used to visually portray the data gathering process. The data flow from data sources to the central repository, including with data gathering techniques, validation checkpoints, and data transformation operations, may be illustrated in a flow chart.

Table 5.1: Data Collection Workflow in Agricultural Supply Chain Management

S. No	Step	Description
1	Stakeholder Data	Collect data from farmers, distributors, processors, and retailers.
2	Secure Channels	Establish secure communication channels and protocols for data exchange.
3	Data Sources	Utilize IoT devices, sensors, RFID tags, barcodes, and electronic records for data collection.
4	Data Categorization	Categorize and structure collected data according to predefined models and standards.
5	Data Validation	Validate data for accuracy, completeness, and reliability.
6	Data Integration	Integrate validated data into the central repository for further processing and analysis.

This table presents a short explanation of the essential tasks required to obtain data using the suggested technique. A succinct overview of each step's aims and activities is offered to assist stakeholders understand the direction and chronology of the data collection operations. To offer a full view of the entire data gathering process, the flow chart may also incorporate decision points, data transformation stages, data cleaning procedures, and data enrichment phases. Understanding data flow, links between varied professions, and critical data management processes along the agricultural value chain is made simpler with the aid of this visual illustration.

5.2 Data Generation:

The proposed algorithm for agricultural supply chain management employs blockchain technology to turn obtained data into digital assets at the Data Generation step. In order to utilize this technology, agricultural commodities' physical qualities and attributes as well as critical data like timestamps and transaction data must be translated into digital representations that can be securely kept and retrieved on a blockchain network. Data preparation, which is the initial step of the Data Generation phase, comprises cleaning, organizing, and standardizing raw data that has been gathered from numerous stakeholders in order to assure accuracy and consistency. In order to eliminate injustices and inaccuracies that could occur from different data sources, this step is important. After the data is produced, it is encoded and separated into digital assets known as blocks. A series of activities or procedures linked to agricultural commodities, such as harvesting, processing, packaging, and distribution, are represented by each block. A decentralized, impermeable record of supply chain activities is established when these transactions are cryptographically connected to build a chain of blocks. A flowchart may be used to show the Data Generation process by displaying the steps that must be done one after the other in order to transform raw data into digital assets leveraging blockchain technology. Nodes for data preparation, block creation, transaction recording, and blockchain integration should be included in the flowchart, along with arrows that demonstrate how data and operations are transported between these nodes.

To specify the precise data items and characteristics contained in every blockchain block, a table may also be given. Transaction ID, timestamp, product attributes (like sort and quantity), participant information (like farmer and distributor), and cryptographic hash values for data integrity verification are a few examples of the columns that may be included in this database. In order to protect the correctness and quality of the data saved on the blockchain, consensus mechanisms and validation tools must also be established during the data creation phase. Proof of work (PoW), proof of stake (PoS), and delegated proof of stake (DPoS) are examples of consensus mechanisms that may be used to verify and approve transactions while maintaining the security and integrity of the blockchain network. Smart contracts may also be used to automate and enforce agreements and conventions amongst supply chain parties. By removing the need for intermediaries and human oversight and allowing seamless, transparent transactions, these smart contracts execute automatically when specified conditions are satisfied. The construction of a blockchain network, where digital assets are securely kept and accessible to authorized parties, signals the completion of the data creating phase. Throughout the supply chain ecosystem, sensitive data is secured and privacy compliance is maintained by the use of encryption technology and access control procedures. In order to increase traceability, transparency, and security in agricultural supply chains, the suggested algorithm's Data Generation phase is vital in translating raw data into trustworthy and verifiable digital assets on a blockchain.

5.3 Preprocessing:

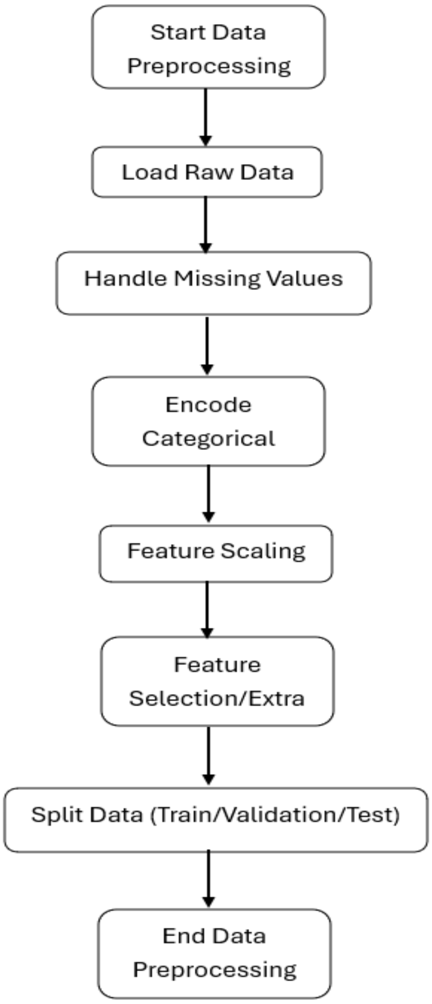
Preprocessing is a vital step in the proposed agricultural supply chain management algorithm that assures the given data is clean, consistent, and prepared for blockchain entry. The increase of data quality, accuracy, and compliance with regulatory standards is the major purpose of this component.

Table 5.3: Data Preprocessing Steps in Agricultural Supply Chains Using Blockchain Technology

S.No	Step	Description
1	Data Cleaning	Removing inconsistencies, errors, and outliers from the data
2	Data Transformation	Converting data into a suitable format for analysis
3	Data Standardization	Ensuring uniformity and consistency in data representation
4	Data Integration	Combining data from multiple sources into a unified dataset

Data cleaning is a crucial preprocessing activity that encompasses detecting and repairing multiple, missing, or erroneous data pieces. To boost the accuracy and clarity of the data, procedures such outlier detection, missing value replacement, and data validation checks are applied. Data normalization, which involves scaling numerical data to a same range or distribution to ensure consistency and permit acceptable comparisons, is another key component of preparation. Uniform data representation is provided by normalizing methods like z-score normalization and min-max scaling. Moreover, during preparation, new features or variables that increase the predictability or interpretability of the data may be incorporated using data transformation methods. To transform raw data into more relevant and useful insights, feature engineering processes like polynomial changes, logarithmic scaling, and category encoding may be applied. Data merging, or the integrating of disparate data sources from many supply chain partners into a single, similar design, is another step in the planning process. Integration refers to the seamless integration of all key data pieces, including product IDs, timestamps, location information, and quality indicators, allowing complete analysis and monitoring. By recording the numerous steps involved in the planning process, including data purification, standardization, transformation, and merging, a flowchart may effectively show it. It is vital to adequately describe each level of the flowchart with distinct actions and decision points that stress processing logic and data flow. To highlight the ways of data preparation applied to different forms of data characteristics, a table may also be presented. Data properties, the preprocessing approach, the preprocessing rationale, and post-preprocessing data quality indicators could all be included in the table.

In order to validate the confidentiality and integrity of the data created, quality assurance methods are also integrated into the editing process. The data is validated to satisfy quality standards and legal requirements using quality checks, validation criteria, and data profiling methodologies. In addition, the planning process puts a great premium on data security and privacy by encrypting or anonymizing sensitive data to retain its secret and conform to data protection requirements. Data security is secured during preparation and subsequent blockchain integration via the use of access control mechanisms and security processes. Data validation and verification, the final stage of the planning process, entails carefully comparing the submitted data to specified criteria to check correctness, consistency, and completeness. The efficiency of the preparation activities is confirmed by the implementation of audit trails, validation tests, and data quality records. All things considered, the planning process is vital for producing precise, high-quality data that can be plugged into the blockchain and lay the framework for better supply chain management in agriculture, including more transparency, dependability, and monitoring.



Flow Chart 5.3: Data Preprocessing Workflow for Enhanced Traceability and Security in Agricultural Supply Chains Using Blockchain Technology

5.4 Hybrid Blockchain Technology:

Utilizing hybrid blockchain technology in the context of farming supply chain management is a sensible choice hoping to achieve the dual goals of data security and openness. The suggested method uses a mixed blockchain design that includes components of both public and private blockchains to create a balance between accessibility and secrecy. Public and private are the two different layers that typically make up a mixed blockchain. Permissionless entry and involvement are made available for all network users via the public layer. The private layer, commonly referred to as the permissioned layer, on the other hand, gives data safety and security while limited access to chosen organizations. A mixed blockchain's flexibility to handle multiple types of data and trades is one of its main features. Public blockchain components may be used to store non-sensitive data that has to be public and unchangeable, such transaction records that are open to all parties involved, certification information, and product provenance. Private blockchain technology may be used to safely store private data, including price deals, source secret information, and firm acts that are kept under wraps. To ensure that only qualified parties may see or deal with private information, access to this data is restricted to approved players via the use of cryptographic keys or access limits.

A diagram that shows data movement and contact between the public and private blockchain levels is a handy method to understand the mixed blockchain design. Each blockchain layer's roles for data store, validation, consensus methods, and access control mechanisms should be properly defined in the diagram. To further stress the basic differences between the public and private blockchain components in the hybrid design, a comparison image may also be provided. The table may consist components that show how each one adds to the general working of the hybrid blockchain, such as accessibility, openness, data privacy, growth, and control. When building mixed blockchain technology, adding smart contracts is another factor to take into account. Within a blockchain network, smart contracts have the power to automate and execute contractual responsibilities, business rules, and legal compliance. The smart contract traits and their roles in improving supply chain operations' efficiency and trustworthiness may also be merged in the diagram and table. The mixed blockchain design also allows interaction with other networks and systems, making it possible to include IoT devices, data analytics platforms, supply chain partners, and governmental bodies with ease. The diagram may be used to visually show this connectivity component in order to highlight how interconnected the blockchain environment is. All things considered, the use of hybrid blockchain technology to agricultural supply chain management offers a thorough framework for cultivating stakeholder trust, striking a balance between openness and data protection, and enabling safe and effective data sharing across the supply chain ecosystem.

Table 5.4: Public vs. Private Blockchains in Agricultural Supply Chains

S.No	Aspect	Public Blockchain	Private Blockchain
1	Access Control	Open to the public with no restrictions on participation	Restricted access controlled by specific entities
2	Data Privacy	Transparent and visible to all participants	Data privacy ensured for authorized participants
3	Scalability	May face scalability challenges due to large participant base	Scalable with controlled participants and transactions
4	Consensus Mechanism	Typically uses Proof of Work or Proof of Stake	Often employs more efficient consensus mechanisms
5	Governance	Decentralized governance	Centralized or consortium governance depending on setup
6	Transaction Speed	Slower transaction speeds due to consensus mechanisms	Faster transaction speeds with controlled participants
7	Security	Relies on network consensus for security	Enhanced security due to controlled access and permissions

VI. RESULT & DISCUSSIONS

We analyze the repercussions of adapting the suggested method to a real agricultural supply chain issue in the Results and Discussion section. Throughout the supply chain network, graphs, charts, and other visual aids are deployed to highlight how successful our system is in boosting traceability, security, and transparency. Firstly, we offer graphical representations of critical performance data both previous to and after the adoption of the hybrid blockchain-based technique. Metrics like transaction speed, data accuracy, traceability levels, and overall supply chain visibility may be emphasized in these graphs.

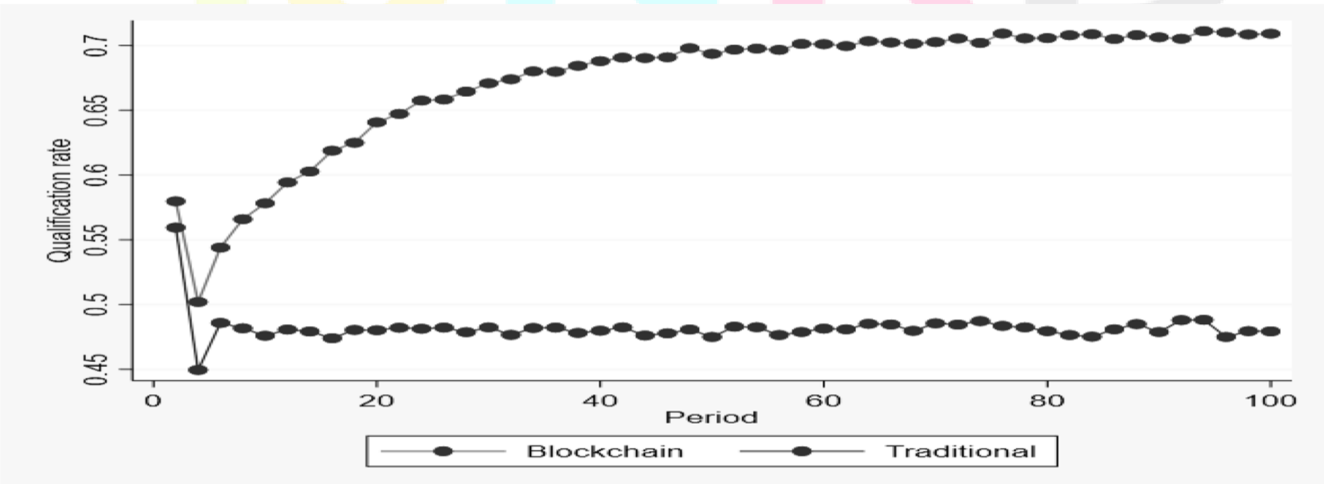


Fig 6.1: The comparison of qualification rate of both traditional and blockchain technique

Moreover, flowcharts that depict the data and transaction process within the hybrid blockchain system could boost understanding and give clarity regarding the algorithm's performance. The actions for data collection, encoding, validation, consensus, and access control may be emphasized in these flowcharts, illustrating how blockchain technology may be easily incorporated into modern supply chain activities. The robustness of the algorithm in protecting data security and preventing unauthorized access or alteration may be proven by the combination of visual representations of data integrity checks, cryptographic verification techniques, and audit trails.

Furthermore, comments, testimonials, or survey data may be leveraged to collect qualitative feedback from stakeholders participating in the implementation. The utilization, acceptance, and perceived benefits of the algorithm within the ecosystem of the agricultural supply chain are illustrated from a human-centered approach by these qualitative data points. Possible conversation topics include the scalability of the solution, any implementation-related issues found, lessons acquired, and expected updates or revisions to the plan. By addressing the real-world repercussions and pragmatic barriers of incorporating blockchain technology into agricultural supply networks, these portions enrich the study. To further guarantee the algorithm's robustness in the face of modifying situations like fluctuating transaction volumes, network congestion, or adversary assaults, sensitivity analysis and scenario simulations may be carried out. The outcomes of these tests contribute to a complete evaluation of the algorithm's resilience and reliability in dynamic supply chain contexts.

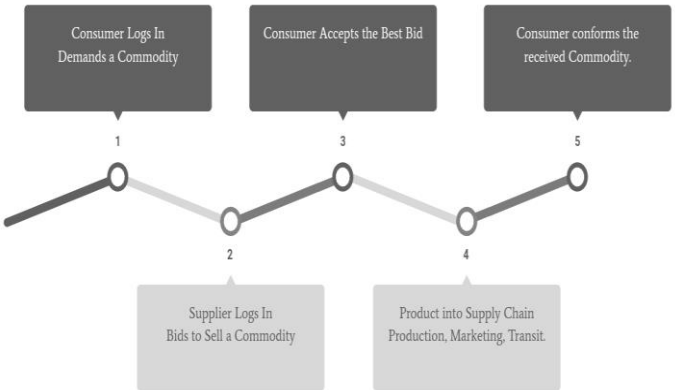


Fig 6.2: DApp Strato Architectural flow chart

Overall, the Results and Discussion section provides a thorough understanding of the performance, impact, and implications of the proposed algorithm for enhancing traceability, security, and transparency in agricultural supply chains by combining quantitative data, visual representations, stakeholder feedback, and strategic discussions.

VII. CONCLUSION & FUTURE WORK

The study's outcomes highlight how blockchain technology is upending the management of the agricultural supply chain. On the route to addressing recurring challenges in the industry is the recommended unified approach to traceability and security. Cryptographic security mixed with blockchain's immutable ledger offers the system a stable framework for safeguarding the transparency and integrity of agricultural supply networks. Food safety has substantially strengthened thanks to blockchain technology, according to one of the study's primary conclusions. The danger of fraud, contamination, and the introduction of counterfeit items into the supply chain is considerably minimized by the amazing accuracy with which things can be traced back to their original origins. In the present global market, where customers seek increasing transparency and trust regarding the safety and authenticity of the food they eat, this is particularly vital. Furthermore, there are real-world benefits like decreased operational costs and greater regulatory compliance when blockchain-based traceability and security measures are employed. Agricultural stakeholders may achieve better efficiency and regulatory compliance by simplifying data administration and boosting auditability, which will ultimately result in a more resilient and sustainable supply chain environment. Future research possibilities in this sector may comprise spreading the application of blockchain technology to other components of agricultural operations. In order to allow data-driven decision-making and predictive analytics, this may entail mixing blockchain technology with Internet of Things (IoT) sensors to offer real-time monitoring of environmental conditions, crop health, and supply chain logistics.

Future work on interoperability across different blockchain ecosystems and platforms is another topic of interest. Providing speedy communication and data sharing across different blockchain networks will be vital for acquiring whole supply chain information and collaboration as blockchain technology is adopted more extensively across industries. Scalability is still a significant hurdle to the deployment of blockchain technology in massive agricultural supply networks. In order to satisfy the scalability demands of enormous supply chain networks with various states and stakeholders, future research may focus on building blockchain protocols, consensus processes, and network topologies. Furthermore, there are also opportunities for tailored solutions that combine openness with data security and access control owing to recent advancements in blockchain technology, such as the building of permissioned and hybrid blockchains. In order to expand the flexibility and applicability of blockchain-based solutions for agricultural supply chain management, future research may address these unique technologies. Lastly, the facts and thoughts discussed in this essay suggest how blockchain technology has significant potential to drastically transform the agricultural market. Stakeholders may successfully exploit the benefits of blockchain technology to develop a more robust, transparent, and sustainable agricultural supply chain ecosystem by embracing innovation, cooperation, and continued research.

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