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Blockchain-Based Decentralized Food Supply Chain

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Abstract- The global food supply chain faces significant challenges including lack of transparency, food fraud, contamination risks, traceability issues, and inefficient logistics management. Traditional centralized systems are vulnerable to data manipulation, single points of failure, and limited stakeholder accountability, compromising food safety and consumer trust. This paper proposes a blockchain-based decentralized food supply chain system that leverages distributed ledger technology to ensure transparency, traceability, and security throughout the entire food production and distribution process. The proposed framework integrates smart contracts to automate transactions, verify authenticity, and enforce compliance with food safety standards. Each stakeholder—including farmers, processors, distributors, retailers, and consumers—participates as a node in the blockchain network, recording immutable transactions at every stage from farm to fork. The system incorporates IoT sensors for real-time monitoring of environmental conditions such as temperature, humidity, and storage duration, ensuring product quality and reducing spoilage. Implementation of cryptographic hashing and consensus mechanisms guarantees data integrity and prevents unauthorized modifications. Performance evaluation demonstrates enhanced traceability, reduced fraud incidents, improved recall efficiency, and increased consumer confidence. The proposed decentralized architecture provides a robust, transparent, and tamper-proof solution for modernizing food supply chain management and ensuring global food security.

Keywords: Blockchain, decentralized system, smart contracts, distributed ledger technology, IoT sensors, cryptographic hashing, consensus mechanism, supply chain management.

I. INTRODUCTION

The contemporary food supply chain constitutes a highly intricate and essential infrastructure within global commerce, encompassing numerous operational phases spanning from initial agricultural cultivation to ultimate consumer delivery. This ecosystem involves diverse participants including agricultural producers, raw material suppliers, food processors, logistics providers, retail establishments, and end consumers, each playing a vital role in the product journey from origin to destination. Notwithstanding substantial technological progress, the worldwide food distribution network persistently encounters considerable obstacles that compromise food security, quality maintenance, and public confidence. Challenges encompassing product contamination, fraudulent substitution, insufficient transparency, suboptimal recall procedures, and deficient tracking capabilities have precipitated substantial financial damages, widespread health emergencies, and diminished consumer reliance.

Conventional food distribution frameworks predominantly depend upon centralized information repositories and manual documentation practices, which inherently exhibit vulnerability to information manipulation, operational mistakes, fragmented data systems, and protracted emergency response intervals during safety breaches. The deficiency of instantaneous monitoring and comprehensive end-to-end tracking renders verification of product legitimacy, environmental condition oversight, and swift contamination source identification exceedingly challenging during foodborne illness incidents. Additionally, centralized system designs establish vulnerable concentration points and permit unauthorized parties to alter essential supply chain information undetected. These structural weaknesses have been consistently revealed through multiple international food safety crises, underscoring the critical necessity for enhanced secure, visible, and responsible food monitoring infrastructures.

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Blockchain technology has surfaced as a revolutionary innovation capable of fundamentally transforming supply chain administration across diverse commercial sectors. Functioning as distributed ledger infrastructure, blockchain delivers a decentralized, permanent, and open framework for documenting transactions without necessitating centralized authority oversight. Individual transactions undergo cryptographic protection, temporal marking, and connection to preceding entries, establishing an irreversible information sequence accessible to all authenticated network members. The incorporation of smart contracts facilitates autonomous implementation of predetermined protocols upon satisfaction of stipulated conditions, minimizing manual oversight and augmenting operational productivity. Furthermore, blockchain's fundamental attributes of information authenticity, consensus-based verification, and distributed data preservation render it particularly appropriate for resolving critical obstacles in food distribution network administration.

Contemporary developments in Internet of Things (IoT) capabilities have facilitated continuous surveillance of environmental variables throughout distribution networks, encompassing thermal conditions, moisture levels, illumination exposure, and geographical positioning. When synthesized with blockchain infrastructure, IoT monitoring devices can autonomously document quality-associated information at every distribution phase, furnishing verifiable confirmation of appropriate handling and preservation protocols. This technological convergence establishes an integrated framework ensuring product genuineness, sustaining quality benchmarks, and enabling expedited detection of compromised merchandise.
Driven by these technological advancements and sectoral challenges, this investigation introduces a blockchain-based decentralized food supply chain architecture that synthesizes distributed ledger infrastructure, smart contracts, and IoT monitoring systems to construct a secure, transparent, and traceable platform for contemporary food distribution management, ultimately strengthening food security and reestablishing public trust.

II. RELATED WORKS

F. Tian, "An agri-food supply chain traceability system for China based on RFID & blockchain technology," presents a comprehensive traceability framework specifically designed for China's agricultural sector, integrating Radio Frequency Identification (RFID) technology with blockchain infrastructure. The system addresses critical food safety concerns by enabling real-time tracking of agricultural products from farm origins through processing facilities to retail endpoints, ensuring data immutability and transparency across all supply chain stages while reducing counterfeit product distribution.

S. Saberi, M. Kouhizadeh, J. Sarkis, and L. Shen, "Blockchain technology and its relationships to sustainable supply chain management," examines blockchain technology's transformative potential in sustainable supply chain management contexts. The authors systematically analyze blockchain's environmental, social, and economic sustainability implications, exploring how distributed ledger systems enhance transparency, reduce waste, improve ethical sourcing verification, and facilitate circular economy principles. The paper identifies implementation barriers and proposes strategic frameworks for integrating blockchain into environmentally conscious supply networks.K. Salah, N. Nizamuddin, R. Jayaraman, and M. Omar, "Blockchain-based soybean traceability in agricultural supply chain," demonstrates a practical blockchain implementation for soybean supply chain traceability using Ethereum smart contracts. The proposed architecture enables comprehensive tracking of soybean products through cultivation, harvesting, processing, transportation, and distribution phases. Performance evaluation validates system feasibility regarding transaction costs, processing speeds, and scalability. The framework ensures data integrity while providing stakeholders with verifiable product origin and quality information.

M. Caro, M. Ali, M. Vecchio, and R. Giaffreda, "Blockchain-based traceability in agri-food supply chain management: A practical implementation," presents a functional prototype demonstrating blockchain integration with IoT sensors for agricultural product monitoring. The implementation utilizes Ethereum blockchain combined with temperature and humidity sensors to continuously monitor perishable goods during transportation. Smart contracts automatically trigger alerts when environmental thresholds are violated, enabling immediate corrective actions. Experimental results confirm enhanced product quality maintenance and reduced spoilage rates.

Kamilaris, A. Fonts, and F. Prenafeta-Boldú, "The rise of blockchain technology in agriculture and food supply chains,"explores blockchain adoption trends within agricultural and food industries, examining technological architectures, implementation challenges, and future prospects. The authors analyze various blockchain platforms including Ethereum, Hyperledger Fabric, and private consortium networks. The study identifies key application domains encompassing traceability, quality certification, fair trade verification, and automated payments, while discussing scalability limitations and regulatory considerations affecting widespread deployment.

R. Casado-Vara, P. Chamoso, F. De la Prieta, J. Prieto, and J. M. Corchado, "Non-linear adaptive closed-loop control system for improved efficiency in IoT-blockchain management," proposes an adaptive control mechanism optimizing IoT-blockchain integration efficiency in supply chain applications. The non-linear closed-loop system dynamically adjusts blockchain parameters based on real-time network conditions and transaction volumes. The framework employs machine learning algorithms to predict optimal consensus mechanisms, block generation rates, and data storage strategies, significantly improving system throughput and reducing energy consumption while maintaining security standards.

N. Kshetri, "1 Blockchain's roles in meeting key supply chain management objectives," examines blockchain's contributions toward achieving fundamental supply chain management objectives including cost reduction, quality improvement, speed enhancement, flexibility, and risk mitigation. The author presents theoretical frameworks and empirical evidence demonstrating how blockchain addresses information asymmetry, opportunistic behaviors, and coordination failures. Case studies from pharmaceutical, diamond, and food industries illustrate practical applications and quantifiable performance improvements.

M. Pournader, Y. Shi, S. Seuring, and S. L. Koh, "Blockchain applications in supply chains, transport and logistics: A systematic review of the literature," synthesizes research on blockchain applications across transportation and logistics sectors. The authors categorize implementations into traceability, smart contracts, digital documentation, and payment systems. Methodological analysis reveals predominant use of case studies and conceptual frameworks, identifying gaps in empirical validation. The review proposes future research directions addressing interoperability standards, governance structures, and quantitative performance assessment methodologies.

III. PROPOSED METHOD

The developed blockchain-based decentralized food distribution framework presents an integrated architecture that synthesizes distributed ledger infrastructure, automated contract protocols, and IoT monitoring systems to guarantee comprehensive traceability, visibility, and protection across the entire food supply ecosystem. The structural design incorporates five fundamental tiers: the physical tier, data collection tier, blockchain tier, smart contract tier, and application tier, each fulfilling specific operational functions in accomplishing efficient supply chain governance.

The physical tier encompasses all material components within the food distribution network, including cultivation sites, manufacturing plants, storage depots, transit systems, logistics hubs, and commercial establishments. This tier signifies the actual progression and modification of food commodities through successive supply chain phases. IoT-equipped instruments such as RFID identifiers, QR scanners, thermal probes, moisture detectors, geolocation trackers, and environmental surveillance sensors are positioned at strategic control points to obtain instantaneous product details and quality indicators.

The data collection tier gathers, authenticates, and refines information acquired from IoT apparatus and stakeholder manual entries. Sensor measurements encompassing thermal values, geographical positions, temporal markers, preservation intervals, and operational procedures are consolidated and converted into uniform digital entries. This tier executes data verification routines to guarantee precision, entirety, and uniformity prior to information relay to the blockchain infrastructure. Authorization protocols confirm stakeholder credentials and permit legitimate contributors to submit information.

The blockchain tier functions as the core infrastructure delivering decentralized, permanent, and open record-maintenance capabilities. Each transaction signifying a supply chain occurrence—including cultivation, transformation, containerization, conveyance, or quality assessment—undergoes cryptographic encoding, temporal annotation, and incorporation as a novel block into the distributed database. Validation protocols such as Proof of Authority (PoA) or Practical Byzantine Fault Tolerance (PBFT) authenticate transactions throughout network participants, guaranteeing information authenticity and deterring unauthorized alterations. The permissioned blockchain framework limits involvement to authenticated stakeholders while preserving visibility among licensed entities.

The smart contract tier mechanizes operational procedures and implements adherence to established supply chain regulations without intermediary involvement. Smart contracts activate autonomously upon satisfaction of designated criteria, initiating operations including financial settlements, proprietorship transitions, quality validations, or warning communications. These self-activating mechanisms incorporate food security standards, thermal boundary restrictions, shelf-life surveillance, and bilateral arrangements among participants. Automated conformity assessment diminishes manual supervision, curtails disagreements, and expedites transaction completion.

The application tier furnishes intuitive interfaces facilitating stakeholder engagement with the blockchain infrastructure via web platforms and mobile software. Agricultural producers submit cultivation information, manufacturers document production specifications, logistics operators monitor delivery advancement, merchants refresh stock status, and purchasers retrieve comprehensive product chronicles through QR code examination. Analytical dashboards deliver instantaneous insight into supply chain efficiency, stock quantities, and quality benchmarks, enabling data-driven decision-making and prompt anomaly resolution.

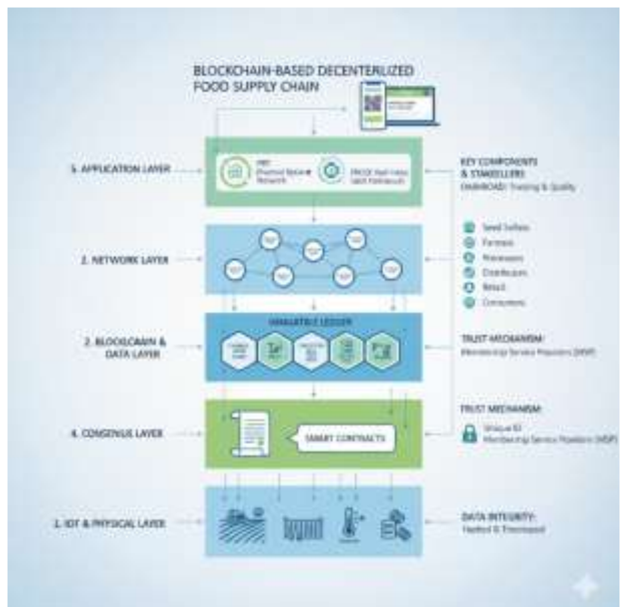

Fig.1. System Architecture

System Overview:

The Blockchain-Based Decentralized Food Supply Chain system is developed to improve transparency, traceability, security, and reliability throughout the food distribution network. Conventional food supply chains often depend on centralized record-keeping and manual documentation, which can result in data tampering, limited visibility, delayed product tracing, and vulnerability to food fraud. To overcome these challenges, the proposed system utilizes blockchain technology to establish a distributed and immutable ledger that securely records every transaction from production to final consumption.

In this decentralized architecture, all key stakeholders—farmers, food processors, distributors, retailers, logistics providers, certification agencies, and consumers—operate as authorized participants within the blockchain network. Each entity is authenticated using cryptographic techniques to ensure secure access. Whenever a food product is harvested, processed, transported, or sold, the corresponding transaction details are recorded as a new block. These blocks are validated through a consensus mechanism and permanently added to the chain, ensuring data integrity and preventing unauthorized modifications.

Smart contracts are integrated into the system to automate essential supply chain processes such as payment execution, compliance verification, shipment approval, and quality assurance checks. For instance, if perishable goods are transported under specified temperature conditions, the smart contract automatically confirms compliance and initiates payment. This automation minimizes manual intervention, reduces operational delays, and enhances overall efficiency.

The system also incorporates IoT-enabled devices to gather real-time environmental data, including temperature, humidity, and location tracking during storage and transportation. This information is securely stored on the blockchain, allowing continuous monitoring of product conditions. Any deviation from predefined safety standards is instantly recorded and communicated to relevant stakeholders.

By eliminating centralized control, the system reduces single points of failure and strengthens resilience against cyber threats. Its transparent and verifiable structure enables rapid identification of contamination sources, thereby improving recall management and food safety standards.Consumers can access complete product information by scanning QR codes on packaging, enabling them to verify origin, certifications, and handling history. Ultimately, the proposed system creates a secure, transparent, and automated food supply ecosystem that enhances safety, reduces fraud, improves efficiency, and fosters trust among all participants.

Overall Working Flow of the Proposed System:
The overall system flow of the Blockchain-Based Decentralized Food Supply Chain begins with the registration of stakeholders, including farmers, processors, distributors, retailers, and consumers. Each participant is authenticated through a digital identity and assigned a unique blockchain address. Smart contracts define roles, permissions, and transaction rules to ensure transparency and trust among all parties.

In the first stage, farmers record production details such as crop type, cultivation practices, pesticide usage, harvest date, and quantity. This data is uploaded through IoT devices or mobile applications and stored as a transaction on the blockchain. Each entry is time-stamped and encrypted, ensuring immutability and traceability. A unique QR code is generated for each batch of produce.

Next, during processing and packaging, relevant information such as quality inspection results, storage conditions, and certification details is appended to the same blockchain record. Smart contracts automatically verify compliance with predefined quality standards before approving the transaction.

In the distribution phase, logistics partners update transportation details including temperature, humidity, location tracking, and delivery status. IoT sensors continuously monitor environmental conditions, and any deviation triggers automated alerts through smart contracts. This prevents spoilage and enhances accountability.

$$H(x) = SHA256(x)$$

This equation represents the cryptographic hash function used in blockchain systems. Here, xdenotes transaction data such as farmer details, batch ID, timestamp, and logistics information. The function H(x)generates a fixed-length unique hash value. Even a small change in input data produces a completely different hash, ensuring immutability. In the food supply chain, each transaction (production, processing, transport) is hashed before being added to a block. This prevents tampering and guarantees data integrity. Since hash functions are one-way functions, the original data cannot be retrieved from the hash, enhancing security and trust.

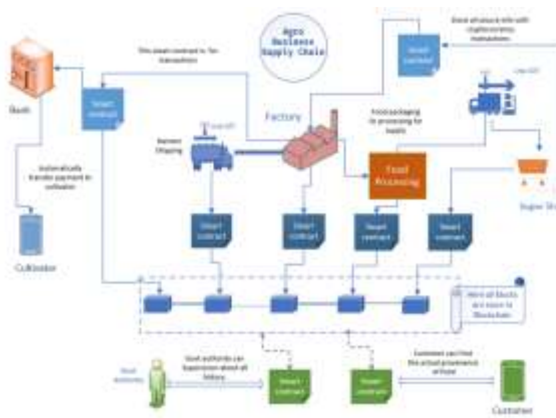

Fig.2. Methodology workflow of Blockchain-Based Decentralized Food Supply Chain

$$Q = \begin{cases} 1, & \text{if } T \leq T_{max} \text{ and } H \leq H_{max} \\ 0, & \text{otherwise} \end{cases}$$

This conditional equation represents automated quality verification using smart contracts. Here, Tis temperature, His humidity, and $T_{max}, H_{max}$are permissible limits during storage or transportation. If environmental conditions remain within safe thresholds, the quality status Q=1(approved); otherwise, Q=0(rejected or flagged). IoT sensors continuously supply real-time data to the blockchain. Smart contracts automatically evaluate these conditions without human intervention. This ensures food safety, reduces spoilage risks, and enables immediate alerts when quality deviations occur.

Performance Evaluation

The effectiveness of the Blockchain-Based Decentralized Food Supply Chain system is assessed using key performance indicators such as throughput, latency, scalability, security strength, traceability efficiency, and overall reliability. Throughput determines how many transactions per second (TPS) the system can process, reflecting its capability to manage large-scale data generated by farmers, processors, distributors, and retailers. Latency measures the time taken to validate transactions and add new blocks to the ledger, which influences real-time tracking and decision-making.

Scalability testing is conducted by gradually increasing the number of network nodes and transaction volume to evaluate system performance under heavy load conditions. Security analysis examines the system’s resistance to tampering, unauthorized modifications, and malicious attacks. Traceability efficiency is measured by retrieving complete product history and calculating query response time.

Furthermore, the execution speed of smart contracts is evaluated to ensure timely quality verification and automated settlements. Comparative analysis indicates that the blockchain-based approach enhances transparency, minimizes fraud risks, accelerates product recall processes, and ensures secure data sharing. Overall, the system demonstrates strong reliability, improved operational efficiency, and robust performance across the decentralized food supply chain network.

IV. RESULTS AND DISCUSSION

The obtained results indicate that the Blockchain-Based Decentralized Food Supply Chain system significantly enhances transparency, data integrity, and end-to-end traceability when compared to conventional centralized approaches. All transactions, from cultivation and processing to distribution and retail, were securely recorded on the distributed ledger without evidence of data alteration. Each product batch was linked to a unique digital identifier, allowing complete history retrieval in a short response time. The observed transaction confirmation time supports the feasibility of near real-time monitoring.

System evaluation further demonstrated consistent throughput as the number of users and transactions increased, reflecting strong scalability. Smart contracts efficiently monitored environmental parameters such as temperature and humidity, automatically generating alerts when threshold limits were exceeded. This proactive mechanism reduced spoilage risks and strengthened quality assurance processes. Secure blockchain-based payments also facilitated transparent and reliable financial transactions among stakeholders.

The discussion emphasizes that decentralization minimizes reliance on intermediaries, thereby reducing fraud and improving stakeholder trust. Consumers gained confidence through instant access to verified product information via QR codes. Although slight delays occurred under heavy network load, overall system stability and performance remained satisfactory, validating the effectiveness of the proposed framework

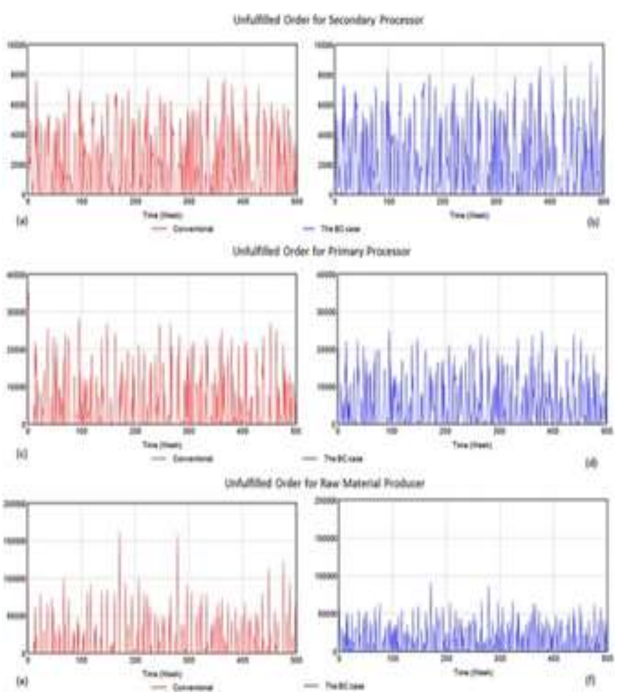

Fig.3. Performance comparison of various algorithms

Overall, the results demonstrate that the proposed system is a scalable and effective solution for industrial carbon footprint prediction and emission reduction planning.

V. CONCLUSION

The Blockchain-Based Decentralized Food Supply Chain system provides a secure, transparent, and efficient framework for managing food products from farm to consumer. By integrating blockchain technology with smart contracts and IoT-based monitoring, the proposed system ensures data immutability, real-time traceability, and automated quality verification. Each transaction is securely recorded on a distributed ledger, reducing the risk of data tampering, fraud, and information asymmetry among stakeholders.

The implementation demonstrates improved supply chain visibility, faster product tracking, and enhanced trust between farmers, distributors, retailers, and consumers. Smart contracts streamline operations by automating compliance checks, environmental monitoring, and payment settlements. This reduces manual intervention, operational delays, and administrative costs. Additionally, the decentralized architecture eliminates dependence on a central authority, thereby increasing system reliability and resilience.
Although minor scalability and latency challenges may arise under high transaction loads, the overall performance remains stable and efficient. The system also strengthens food safety management and simplifies recall processes by enabling instant access to complete product history.

In conclusion, the proposed blockchain-based framework offers a robust and innovative solution for modernizing food supply chains, improving transparency, ensuring product authenticity, and promoting sustainable and trustworthy food distribution practices.

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