Journal of Experimental Agriculture International

Volume 46, Issue 5, Page 636-653, 2024; Article no.JEAI.115611
ISSN: 2457-0591
(Past name: American Journal of Experimental Agriculture, Past ISSN: 2231-0606)

Role of Blockchain Technology in Enhancing Supplychain Traceability, Transparency and Efficiency

Sunanda Doshi [a*], Sudhanshu Jangir [b++] and Prakashsinh Gohil [b#]

[a] *MBA-AVCM (Agripreneurship and Value Chain Management), Indian Institute of Sustainability Gujarat University Ahmedabad, India.*
[b] *Indian Institute of Sustainability, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JEAI/2024/v46i52419

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/115611

Review Article

Received: 03/02/2024
Accepted: 07/04/2024
Published: 09/04/2024

ABSTRACT

The conventional traceability system faces challenges such as centralized control, lack of transparency, unreliable data, and the frequent creation of information silos. To address these issues, this paper introduces a blockchain-based traceability system tailored for the storage and retrieval of product information in the agricultural supply chain. Utilizing blockchain's inherent properties of decentralization, immutability, and traceability, this system enhances the transparency and trustworthiness of traceability data.
Furthermore, the integration of blockchain technology with cryptography is suggested to enable the secure exchange of private information within the blockchain network. Additionally, we have developed a reputation-based smart contract system to motivate network participants to contribute

++ *Director;*
\# *Research Scholar;*
**Corresponding author: E-mail: parikh_sunanda@hotmail.com;*

traceability data actively. This approach aims to leverage blockchain's capabilities to overcome the limitations of traditional traceability systems in the agricultural sector.

This research paper explores the role of blockchain technology in enhancing supply chain transparency and efficiency, focused on food and agriculture sector. It underscores the growing consumer demand for authentic product and the challenges of maintaining transparency is increasingly becoming difficult in global and complex markets.

Findings reveal that blockchain has significant capabilities to increases transparency, traceability, and security, while potentially reducing costs and errors. However, the study also identifies challenges, such as technological complexities, scalability issues, regulatory uncertainties, and integration hurdles.

A strategic framework for adopting blockchain in retail supply chains is proposed, offering insights for practitioners and policy considerations. The paper also designs a novel traceability system for agricultural product supply chains, employing blockchain technology to address issues such as centralized management, opaque information, and data unreliability.

The study concludes that while blockchain technology presents significant opportunities for transforming supply chains, realizing its full potential necessitates careful strategizing and sector-wide collaboration. The research offers recommendations for practitioners and outlines directions for future research, highlighting that the successful application of blockchain hinges on organizational adjustments and meeting specific boundary conditions.

Keywords: Supplychain; blockchain; cryptography; traceability; dAPP; DAO; smart contract; transparency; efficiency; consensus protocol.

1 INTRODUCTION

In light of the projection that the Supply Chain Industry Analytics Market is set to expand at a Compound Annual Growth Rate (CAGR) of 16%, reaching a valuation of US $10 billion by 2025, it is imperative to address the operational inefficiencies plaguing this sector.

From the point of view of Agri and food sector it is to be noted that the world population is projected to reach 8.5 billion in 2030, and to increase further to 9.7 billion in 2050 and 10.4 billion by 2100. Obviously Food demand will also go up with the population. With this the child ratio, senior citizen ratio and other ratios are going to increase with that pace. No prediction can be made without proper technology. Demand-supply ratio if not maintained, sustainable growth is just not possible. Supply chain should be strong enough to handle the issue, but more important is block-chain. Technology that's strong enough to be altered, manipulated and compromised.

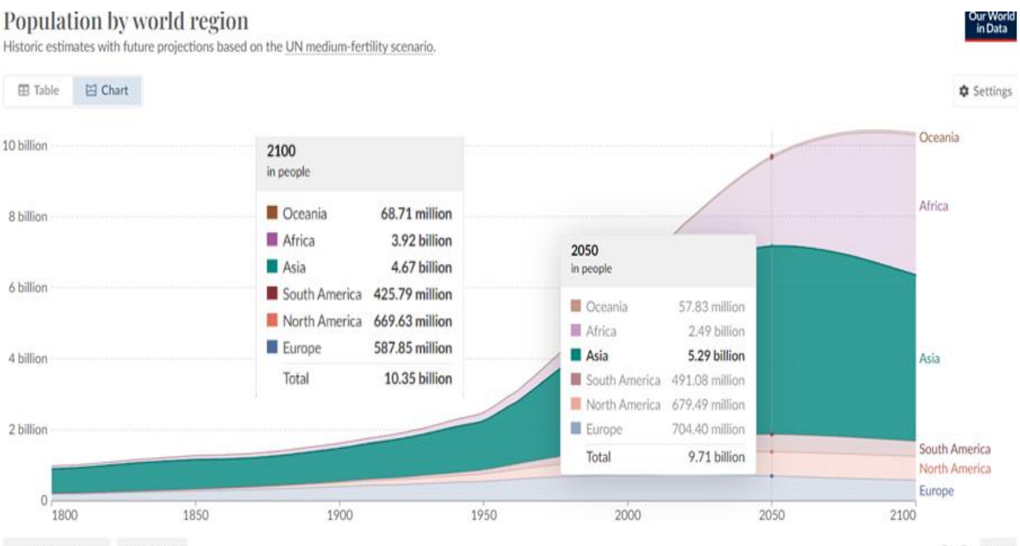

Fig.1. Population by World region [4]

Image 1. Need of the World in 2030

Notably, major freight companies, which rank among the world's largest businesses, continue to rely heavily on archaic systems characterized by the use of physical documentation. This reliance on legacy processes poses significant operational challenges, primarily due to the time-intensive nature of manual paperwork processing. Such methods are not only inefficient but also heighten the risk of document misplacement, which in turn can lead to substantial delays and increased transaction costs as stakeholders endeavour to trace and verify transactions through repetitive communication for document copies.

These challenges are multifaceted, stemming from both technical and organizational inadequacies, and they profoundly affect the efficiency, transparency, and reliability of supply chain operations.

The key issues encompass:

1.1 Data Silos

A prevalent issue arises from various stakeholders within the supply chain utilizing disparate data management systems. This leads to the formation of data silos, obstructing efficient data sharing and analysis, thereby diminishing visibility throughout the supply chain.

1.2 Data Quality and Accuracy

Consistently maintaining high-quality and accurate data is a formidable challenge. This issue is compounded by manual data entry errors, the prevalence of outdated information, and the lack of uniform data standards among diverse supply chain entities.

1.3 Lack of Real-Time Data

The deficiency in obtaining real-time data in many supply chains hampers prompt decision-making, crucial for adapting to market shifts or operational disruptions.

1.4 Integration Issues

The integration of varied technologies and systems across multiple supply chain partners is a complex and often expensive endeavor. This complexity is further amplified by the need to standardize data formats and ensure compatibility across diverse IT systems.

1.5 Scalability

Escalating challenges are faced in scaling data infrastructure to accommodate growing data volumes and increasingly intricate network requirements, as supply chains expand and evolve.

1.6 Security and Privacy Concerns

The safeguarding of sensitive supply chain data against cyber threats, along with ensuring adherence to data privacy regulations, is a significant concern. The distributed nature of supply chains exacerbates their vulnerability to data breaches and cyber-attacks.

1.7 Lack of Transparency and Traceability

Achieving comprehensive visibility within the supply chain is frequently challenging due to the absence of a unified platform for tracking products and transactions. This lack of transparency can result in inefficiencies and risks, such as the circulation of counterfeit products or compliance issues.

1.8 Reliance on Legacy Systems

The persistent reliance on outdated systems, ill-equipped to meet contemporary data demands, impedes the adoption of novel technologies and data-driven methodologies within the supply chain.

1.9 Data Analytics and Utilization

While data collection is a significant aspect, the effective analysis and utilization of this data to derive actionable insights represent an additional challenge. Many organizations lack the necessary expertise or tools to analyze complex data sets comprehensively.

1.10 Interoperability between Different Technologies

With the increasing integration of advanced technologies like the Internet of Things (IoT), Artificial Intelligence (AI), and blockchain into supply chains, ensuring seamless interoperability among these diverse technologies is critical.

Addressing these challenges is vital for enhancing the operational efficiency and strategic decision-making capabilities within the supply chain sector, especially in an era where data-driven insights are pivotal to competitive advantage and organizational success.

2. Supplychain Problem Case studies

Supplychain is applicable to each and every industry in view of high globalization and nationalization. In view of this scope has been defined as Food Supply Chain to remain most relevant to the specialization of Agriculture domain.

The multifaceted nature of risks within the food supply chain extends beyond the realm of bacterial contamination, as underscored by an article detailing the 10 Most Significant Food Recalls in U.S. History. [1] It delves into the array of challenges encountered in the food supply sector, including the presence of unlisted ingredients (such as horse meat, non-halal substances, or inaccuracies in organic food labelling),[2] discrepancies in the stated origins of products, erroneous date and production information, and lapses in maintaining acceptable standards for food production and animal welfare. The gravity of these issues is exemplified by the World Health Organization's estimate that in 2010, approximately 582 million individuals globally suffered from foodborne illnesses, representing nearly 1 in every 14 people, with some cases resulting in fatalities.

Given these concerns, it becomes increasingly clear that the supply chain sector urgently requires a fully automated and reliable system. Such a system should address not only current challenges but also pre-empt future issues arising from inadequate transparency, traceability, and efficiency within the supply chain. This paper posits that implementing robust, technologically advanced solutions is imperative to mitigate risks, ensure consumer safety, and maintain trust across various supply chain domains

Based on above it is quite evident that Supply Chain needs fully automated, trustworthy system to address current as well as future problems which are arising out of inadequate transparency, traceability and efficiency.

2.1 Challenges in Supplychain of Potatoes – A Local Real Life Case Study

2.1.1 Product, raw material, supplier and purchaser

Potato Supplier – APMC Member at Ahmedabad APMC Potato Order Placed by (Purchaser)– Namkeen/Snacks Manufacturer Product for which Potato to be ordered – Potato Chips

2.1.2 Scope of contract

Potato Supplier is to deliver demanded quantity of potatoes to the Namkeen Manufacturer as and when required. Quality of Potatoes required were primarily having following terms.

(1) Size of Potato – All Potatoes should be in specified range of diameter
Size Exception : Small size potatoes can also be supplied to contractors if there is a provision in contract that the batch will be used for other purpose than chips. A lower rate payment will be made.
(2) Starch Level – All Potatoes should have a starch level in specified range which was

found ideal for quality potato chips manufacturing.

(3) Colour of Potato – If Potato supply found in different colour like be green, brown patches, rings, stains, either entire batch rejection will happen or if part of the batch is not as per the standards then manual removal of defective potatoes to be done by Potato Supplier

2.1.3 Order fulfilment model

1. Potato Supplier opted for Contract farming to manage the required quality and production quantity of Potatoes.
2. Supplier decided to acquire Cold Storage to supply the committed stock in non-season in uninterrupted manner from Cold Storage.

2.1.4 Stake holders

Farmer, Purchaser, Suppliers, Cold Storage, Testing Team, Logistic Team

2.2 Challenges faced by Potato Supplier

A Well-Defined schedule (week wise procuring seed to delivery of potatoes to Supplier) as a part of Contract Farming. All terms were prepared and explained to respective stake holder by the Potato Supplier. The Process chain and eco system involved in schedule includes activities right from the crop planning - selection of “seeds” of potato, irrigation, manure, pesticide application. It was well prepared but it was completely manual and hence at the end of the cycle there was no surety that quality of potato will be as desired, as demanded by purchaser.

As per the Quality standards established by Potato Supplier/s, samples were taken from each batch of potatoes and chips were manufactured in house-hold manner before taking decision that whether the batch can be sent to snacks Manufacturer or not. This Process was established just to avoid rejection due to sizable logistics cost. Now two conditions apply here if batch is as per standards, potatoes will go to processors/cold storage for future/further use, second if Potatoes are not as per standards required for chips, the batch will go in local market for sale.

2.2.1 Cold Storage

There was one more entity getting involved - Cold Storage. In the season, all extra quantity of potatoes beyond the demand were transferred and stored in cold storage under pre-defined environment of temperature and humidity in particular.

As a result, two new logistics need arose (1) From Farm to Cold Storage and (2) Cold Storage to Manufacturer.

Subsequent effect - separate logistic supply chain routes, methodology and cost.

During off-season of potato crop, supply need to be provided from Cold Storage.
Following new challenges were added.

(1) Difference in Weight - Weight of potatoes which were measured at time of receipt in cold storage and same set of potatoes weight were different at the time of delivery.
(2) Certain quantity of Potato used to get degraded to a level that they were not at all useable.

Thus, there was extra quality check required and process chain become different than parent process chain. The route of delivery was also different because location of APMC and Cold Storage were quite at a distance. This added extra cost, Quality and logistic related challenges.

2.2.2 Observations

(1) All stake holders were managing system in silos.
(2) Number of activities were performed in manual mode, unmonitored mode, uncontrolled mode by each Stake Holder.
(3) At farmer level it was more of informal way to work on what is agreed in contract i.e. there was more or less no system in place.

3. CONCEPTS AS WELL AS CHARACTERISTICS OF TRACEABILITY AND A FOOD TRACEABILITY SYSTEM

The concept of 'traceability' is defined in various ways across different scholarly sources, as highlighted by Bosona & Gebresenbet (2013), Karlsen et al. (2013), and Olsen & Borit (2013). This diversity in definitions indicates a lack of universal consensus about the term's meaning. To establish a clear foundation for this study, it was necessary to define 'traceability' upfront, aligning our understanding and approach. Predominant traceability standards, such as those from the EU (2002), ISO (2007, 2018), typically emphasize the ability to track critical attributes of a product from its origin, including its ingredients, to the final step in the supply chain. Olsen and Borit's (2013) analysis reveal that the various definitions of 'traceability' in literature generally encompass two or more of these key aspects: uniformity and precision in the terminology used (e.g., distinguishing between 'tracking' and 'tracing'), the backward tracing of ingredients, the forward tracking of products, and the documentation of product history throughout the supply chain.

As our focus is the activities to be performed by using blockchain for traceability, we adopt the definition of (Bosona & Gebresenbet, 2013, p. 35) in which the traceability activities are brought in direct relation to logistics activities:

"*Food traceability is part of logistics management that capture, store, and transmit adequate information about a food, feed, food-producing animal or substance at all stages in the food supply chain so that the product can be checked for safety and quality control, traced upward, and tracked downward at any time required.*"

Viewing food traceability as a component of logistics management underscores the link between food safety, quality assurance, and the efficacy of logistics operations. This connection is particularly evident in instances of food recalls, a topic frequently discussed in literature (Bosona & Gebresenbet, 2013). Although having comprehensive traceability information is crucial for effective recall processes, the efficiency of these processes also relies heavily on well-orchestrated logistics operations and the degree of coordination among various actors in the supply chain (Bourlakis & Bourlakis, 2006; McCallum, 2012).

While some definitions of traceability concentrate mainly on its core functions of tracking as well as tracing, Bosona and Gebresenbet's definition explicitly ties the purpose of traceability (ensuring safety and quality control) with its conditions of use (applicability at all stages and any required time). Depending on the flow of information, traceability can be split into forward traceability ("tracking") and backward traceability ("tracing") (Olsen & Borit, 2013). The distinction becomes clear in a product recall scenario: Tracking enables the monitoring of products all over the supply chain from start to finish, identifying them based on recall criteria. Conversely, tracing allows for pinpointing a product's origin and thus understanding the relationship between the various components that make up the product Blockchain A Technology Connect wrt Transparency, Traceability and Effectiveness [3].

Blockchain is considered as The most disruptive technology in decades. At core Blockchain is a distributed data store. *Harvard Business School titled it as Foundational Technology.*

Blockchain is a distributed ledger, a database of transactions that is shared and synchronized across multiple computers (identified as Node) and locations – without any centralized control. Each party owns an identical copy of the record, which is automatically updated as soon as any additions are made.

Blockchain technology is structured to be inherently resistant to data modification, showcasing a distributed computing system with a high level of Byzantine Fault Tolerance and crowd consensus. Once data is recorded in a block, it cannot be retroactively changed without modifying all following blocks, a process that would necessitate the agreement of the majority of the network.

A distributed ledger efficiently records transactions between two parties in a manner that is both verifiable and permanent. It is typically managed by a peer-to-peer network that collectively follows a protocol for the validation of new blocks.

The mechanism underlying blockchain makes it a reliable and tamper-proof platform for exchange of sensitive information. As the blockchain relies on no centralized point of access, it has no single point of failure and is virtually hack-proof.

Every node in a decentralized system has a copy of the blockchain. Data quality is maintained by massive database replication_and computational trust.

Blockchain is also considered as Notarised Ledger, Triple Entry Accounting System, Value Exchange Protocols based technology, Decentralized Technology.

Two types of blockchain Private and Public (Permissioned and Permission less) Choose - Allow *anyone* to write to your block chain, or known, vetted participants give needed option for block chain stakeholders to be on one page and still remain in control of what each one is supposed to do.

Smart contract is capability as a specialized computer code. Computer Program which works like a self-operating system that automatically gets executed when specific conditions are met without any possibility of intervention or censorship, downtime, fraud or third-party interference. This really offers immutability.

Transparency is achieved with actions and decisions are recorded on the blockchain. DAOs (Decentralised Autonomous Organization) operates autonomously and is governed by a set of rules encoded into smart contracts, eliminating the need for centralized control, decisions are made democratically through a consensus mechanism, typically involving stakeholders who hold and use tokens as voting rights.

Consensus Protocol (*consensus algorithm, consensus mechanism, consensus method*) ensures the which users block will be published. Whenever a new transaction gets broadcasted to the network, nodes have the option to include that transaction to their copy of their ledger or to ignore it. When the majority of the actors which comprise, the network decides on a single state, consensus is achieved. It is a process to achieve agreement within a distributed system on the valid state.

Immutability through Integrity and Security is offered through Three types of integrity namely (a) Ownership (b) Transaction and (c) Order is assured through using Public Key-Private Key, Transaction Chain and cryptography as well hash. ISO 27001 is considered as most renounced standards for Information Security. It has three dimensions Confidentiality, Integrity and Availability. Blockchain ensures Confidentiality through Encryption and Access Control, Integrity through Write as append mode only as well as no change possible for earlier transaction and availability through multiple copies in world all across and hence no question arises for single point failure.

Table 1. Supply chain issues Vs blockchain strength

Supply chain Transparency and Traceability Issues	Block Chain Strength
easy data manipulation,	Ledger exists across a network.
a lack of openness and reliability	It protects the communication (information) shared between the parties.
An ineffective transmission	Distribute and copy the transactions to each and every computer that have participated in blockchain.
Easy to hack	It duplicates all transactions across the network so transactions cannot be modified nor cannot be manipulated.
Duplication of data	Blockchain ledgers are hard to be hacked.
No time stamp	Time stamp always there.

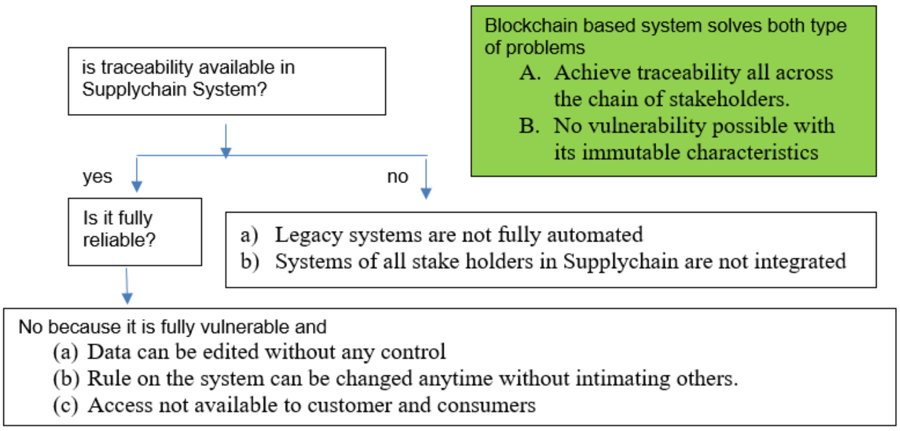

Fig. 2. Supply chain transparency

3.1 Supplychain Transparency through Traceability

Several key characteristics of blockchain technology has capability to significantly improve supply chain traceability and transparency through its right utilization.

Immutability: Every transaction and step in the supply chain journey are recorded on the blockchain in chronological order, creating an irreversible and tamper-proof audit trail. This makes it impossible to fraudulently alter or manipulate data, enhancing trust and accountability.

Transparency: All participants in the supply chain, from producers to consumers, can access a shared view of the data. This promotes transparency and collaboration, allowing stakeholders to track product movement, origin, and quality in real-time.

Decentralization: Unlike centralized databases, blockchains distribute data across a network of nodes. This eliminates single points of failure and censorship, ensuring continuous access to information even if specific nodes go offline.

Traceability: The linked nature of blockchain transactions enables precise tracking of products as they move through the supply chain. This allows for pinpointing issues, identifying contamination, or verifying authenticity quickly and efficiently. (https://www.sciencedirect.com/science/article/abs/pii/S0377221722004076)

Sensor integration: Blockchain can integrate with sensors and IoT devices that track environmental conditions, product status, or location data. This real-time information can be automatically recorded on the blockchain, further enhancing transparency and traceability. (https://www.mdpi.com/1424-8220/23/2/788)

Smart contracts: These self-executing code units automate specific actions based on pre-defined conditions. They can manage tasks like triggering payments upon delivery, enforcing ethical sourcing practices, or ensuring product quality meets agreed-upon standards.

Data security: Blockchain's strong cryptographic algorithms and consensus mechanisms protect data from unauthorized access and manipulation. This builds trust and protects sensitive information throughout the supply chain.

Efficiency: Streamlining processes and eliminating intermediaries with automation can lead to faster transactions, reduced costs, and improved operational efficiency within the supply chain. [4,5]

Sustainability: By recording information about ethical sourcing, sustainable practices, and carbon footprint, blockchain can promote responsible supply chain management and enhance environmental sustainability.

Consumer trust: Increased transparency and access to information empower consumers to make informed choices about the products they purchase. This can lead to greater trust in brands and products that utilize blockchain-based supply chain systems.

4. OP CHARACTERISTICS OF BLOCKCHAIN TECHNOLOGY

1 Decentralization: Unlike traditional systems controlled by centralized entities, blockchains distribute data and processing power across a network of independent nodes. This makes them resistant to censorship, manipulation, and single points of failure.

2. Immutability: Once data is recorded on a blockchain, it becomes virtually impossible to alter or delete. This creates a tamper-proof audit trail, ensuring transparency and trust in the recorded information.

3. Security: Cryptography, hashing algorithms, and consensus mechanisms work together to secure blockchains. Strong encryption protects data from unauthorized access, while distributed consensus ensures data integrity and consistency across the network.

4. Transparency: All transactions and data on a public blockchain are visible to everyone on the network. This transparency fosters accountability and reduces the risk of fraud or manipulation.

5. Efficiency: Blockchains can automate complex processes and eliminate intermediaries, streamlining workflows and potentially reducing transaction costs.

6. Traceability: Each transaction on a blockchain is linked to the previous one, creating an

immutable chain of evidence. This makes it easy to track the movement of assets and identify the origin of transactions.

7. Auditability: The transparency and immutability of blockchains enable comprehensive auditing of recorded data. This helps ensure accuracy, compliance, and builds trust in the system.

8. Programmability: Smart contracts, self-executing code stored on the blockchain, automate agreements and transactions based on pre-defined conditions. This eliminates the need for third-party intermediaries and facilitates trust-less interactions.

9. Global Reach: Blockchains operate without geographical boundaries, enabling seamless cross-border transactions and communication. This can democratize access to financial services and other opportunities.

10. Innovation: Blockchain technology is still evolving, with new applications and use cases emerging constantly. Its potential to disrupt various industries and revolutionize existing systems is vast and holds immense promise for the future.

4.1 How Blockchain will Solve the Problems?

Based on the blockchain technology capabilities, areas of supply chain management that can benefit from the blockchain are (a) Recording the type and quantity of goods being shipped (b) Tracking orders (c) Automation of processes such as payment (d) Helping to prioritize orders (e) Providing shipping information (f) Preventing Fraud (g) Increased Safety (h) Authenticating goods [6].

The food industry: is going to see its supply chains revolutionized by blockchain technologies. immutable records will help ensuring food safety standards, reduce food waste along with accurate use-by dates, etc.

Blockchain technology offers innovative solutions to many of the challenges faced in supply chain management, leveraging its inherent characteristics like decentralization, transparency, and immutability. Here's how blockchain can address each of the specific challenges:

Data silos: Blockchain creates a decentralized ledger that is accessible to all participants in the supply chain. This shared ledger ensures that data is not confined to individual silos but is available across the network, enhancing collaboration and visibility.

Data quality and accuracy: The immutability of blockchain records ensures that once data is entered, it cannot be altered, enhancing the reliability and accuracy of the data. Smart contracts can automate data entry processes, reducing human errors.

Lack of real-time data: Blockchain networks can provide real-time updates to all participants. This is especially useful for tracking product movements and inventory levels, allowing for more agile decision-making and responsiveness. [7]

Integration issues: A blockchain platform can act as a universal, interoperable layer that integrates with different systems used by various supply chain stakeholders, ensuring seamless data exchange and consistency.

Scalability: Many blockchain solutions are designed to be scalable, accommodating the growing amount of data and increasingly complex networks in supply chains without compromising performance [8].

Security and privacy concerns: Blockchain's secure, tamper-proof nature helps protect data against unauthorized access and cyber threats. Privacy can be managed through permissioned blockchains, where access to sensitive data is controlled.

Lack of transparency and traceability: Blockchain provides a transparent, end-to-end view of the supply chain. Every product movement or transaction is recorded on the blockchain, enabling complete traceability and accountability.

Reliance on legacy systems: Blockchain can be integrated with legacy systems to enhance their capabilities. This integration helps modernize and digitize traditional supply chain processes, bringing them in line with contemporary data needs.

Data analytics and utilization: By providing a single source of truth, blockchain simplifies data analytics, as the data is standardized and readily accessible. This can enable more effective data-driven strategies and insights.

Interoperability between different technologies: Blockchain can serve as a foundational technology that connects various emerging technologies like IoT, AI, and RFID in the supply chain, ensuring they work seamlessly together.

In summary, blockchain offers a robust framework for addressing many of the prevalent data-related challenges in supply chains. Its ability to bring transparency, efficiency, and security is particularly valuable in complex, multi-stakeholder environments typical of modern supply chains. However, successful implementation requires careful planning, technological integration, and collaboration among all supply chain participants.

5. CREATING A CUSTOMISED VERSION OF BLOCKCHAIN TECHNOLOGY FOR SCM

Known participants: Supply chains are best served by private blockchains among recognized entities, rather than open blockchains with anonymous participants. This ensures that each inventory unit is securely linked to its specific owner at each stage, allowing supply chain members to verify the origin and quality of their inventory. Consequently, only pre-approved parties should be allowed in such a blockchain, necessitating a permission-based system for companies to join.

Selective permission granting is essential due to the inherent data privacy risks in blockchain's open and decentralized nature. Any participant in a blockchain can access transaction data, and as this data accumulates, it could be exploited for competitive intelligence, stock trading, or market prediction. For security, participants in the blockchain must undergo thorough vetting and approval.

Establishing a trusted network of partners for data sharing on a blockchain involves overcoming various obstacles. These include developing a governance system to set rules on network membership, data sharing, encryption, access rights, dispute resolution, and the usage scope of IoT and smart contracts. Another challenge is managing the impact of blockchain on pricing and inventory decisions, as it increases transparency about product quantity or age in the supply chain. The repercussions of this transparency on costs and benefits within the supply chain are difficult to foresee.

For these reasons, the companies we examined focused on specific applications like tracing drugs and food products and managing accounts payable. These applications have clear use cases or regulatory mandates. To mitigate data privacy risks and gain acceptance from supply chain partners, these firms limit the types of information recorded on the blockchain.

Simpler consensus protocols: Blockchain technology mandates a consensus protocol, a system that ensures everyone agrees on a single, consistent transaction history. In decentralized cryptocurrency networks, which lack a central authority, a complex system known as proof of work is used. This method secures the agreement of the majority on network transactions, but its complexity slows down the addition of new blocks. This slowness renders it impractical for the high speed and volume of transactions typically found in supply chains.

However, in a private, permissioned blockchain, the proof-of-work method isn't necessary for achieving consensus. Simpler mechanisms can be employed to decide who gets to add the next block. An example is the round-robin protocol, where the privilege to add a block circulates among participants in a predetermined sequence. As all participants are known entities, any malicious attempt to alter the chain unfairly during one's turn would be quickly identified. Moreover, any disagreements can be efficiently resolved by participants through the validation of preceding blocks.

Security of physical assets: Even with the security of blockchain records, there's still a risk of contaminated or counterfeit products being erroneously or maliciously tagged and integrated into the supply chain. Additionally, inventory data may be compromised due to errors in scanning, tagging, or data entry.

To mitigate these risks, companies are adopting three strategies. Firstly, they perform rigorous physical audits at the point of entry into the supply chain, ensuring that the actual shipments align with blockchain records. Secondly, they develop distributed applications (dApps) that monitor products throughout the supply chain. These dApps verify data accuracy and interact with the blockchain to minimize errors and fraud. If a counterfeit or mistake is identified, the blockchain's transaction history for that item aids in tracing it back to its origin. Thirdly, companies enhance blockchain reliability by employing IoT devices and sensors. These automatically scan products and update the blockchain records, reducing the need for human input.

In the realm of asset trading, such as digital books and music, tokenization alone is effective in ensuring trust and security. When ownership of these digital assets is linked to a blockchain platform, the risk of counterfeits is virtually eliminated. For example, universities often use digital reading materials for courses, collaborating with publishers and copyright holders. Incorporating this digital supply chain into a blockchain platform equipped with smart contracts could significantly boost efficiency, enabling smooth access to products, ownership verification, and streamlined payment processes

6. DESIGN OF BLOCKCHAIN BASED TRACEABILITY SYSTEM

The architectural framework, as shown below for agricultural product's traceability system in blockchain is primarily segmented into four layers: the storage layer, the service layer, the interface layer, and the application layer, as depicted in Fig. 3.

The agricultural products blockchain traceability system is organized into several layers, each with specific functions. The storage layer encompasses Three databases namely (1) MySQL, (2) the system's local database, and (30 the CouchDB database integrated with the blockchain system. The local database holds the public information from each step of the process, while the blockchain system securely stores private information as encrypted text and public information as hash values. This setup facilitates quick data queries and minimal storage space on the blockchain, ensuring private information's security and allowing for authenticity checks against potential tampering.

The service layer includes various components primarily four components namely (1) data analysis, (2) reputation-based smart contracts, (3) key management and authorization, and (4) the PBFT (Practical Byzantine Fault Tolerance) consensus mechanism. The interface layer is made up of smart contracts responsible for uploading data to the blockchain system and handling data queries. These contracts are programmed to automatically execute when labels are printed and to respond to queries from the terminal.

Lastly, the application layer caters to the diverse needs of the system's users. It offers business functionalities tailored to different participants, such as data upload for enterprises at various stages of the supply chain, traceability information queries for consumers, and monitoring capabilities for government authorities

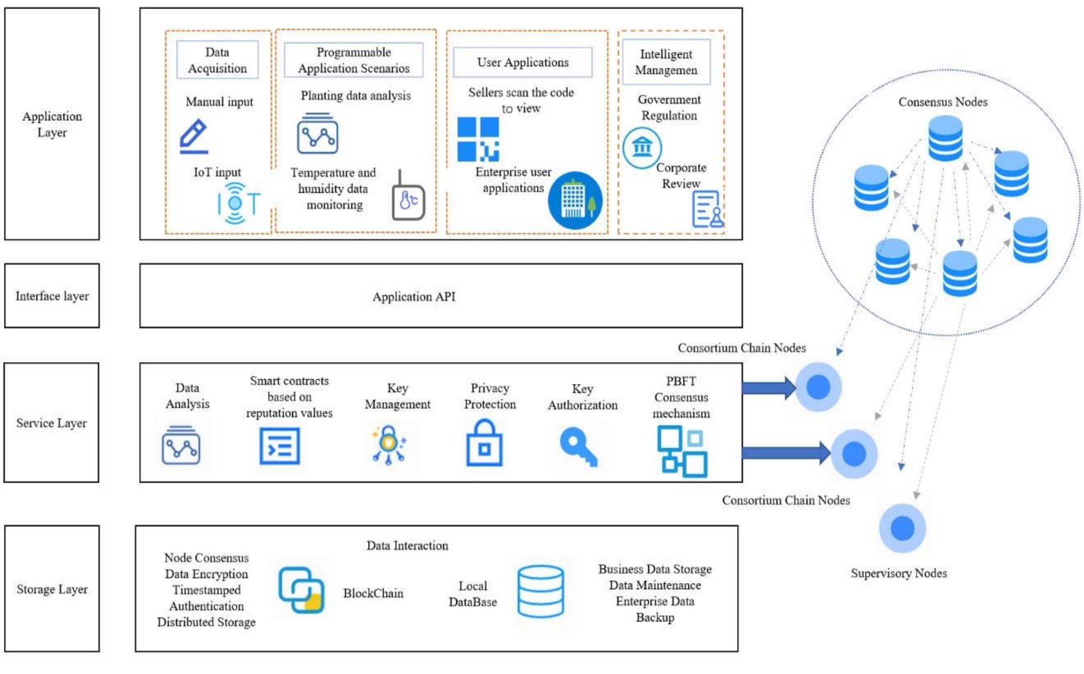

Fig. 3. Architectural framework of the blockchain traceability system [9]

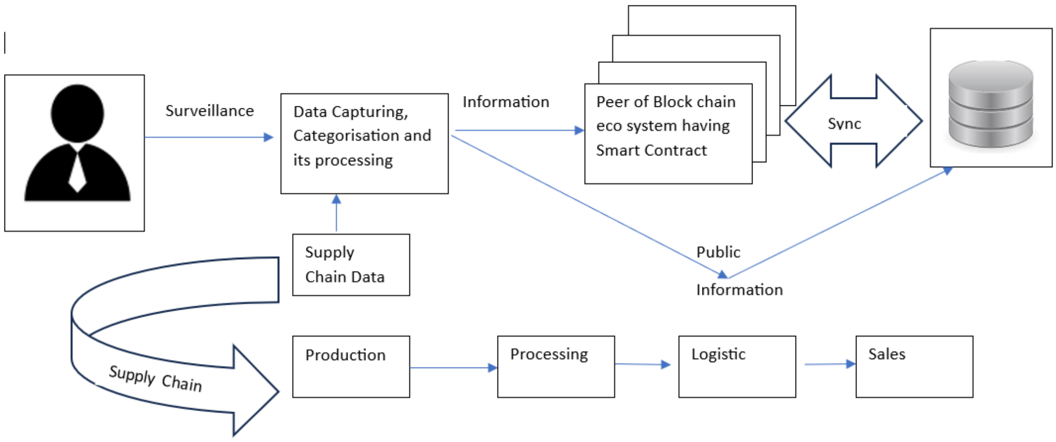

Fig. 4. Data collaboration storage flow diagram

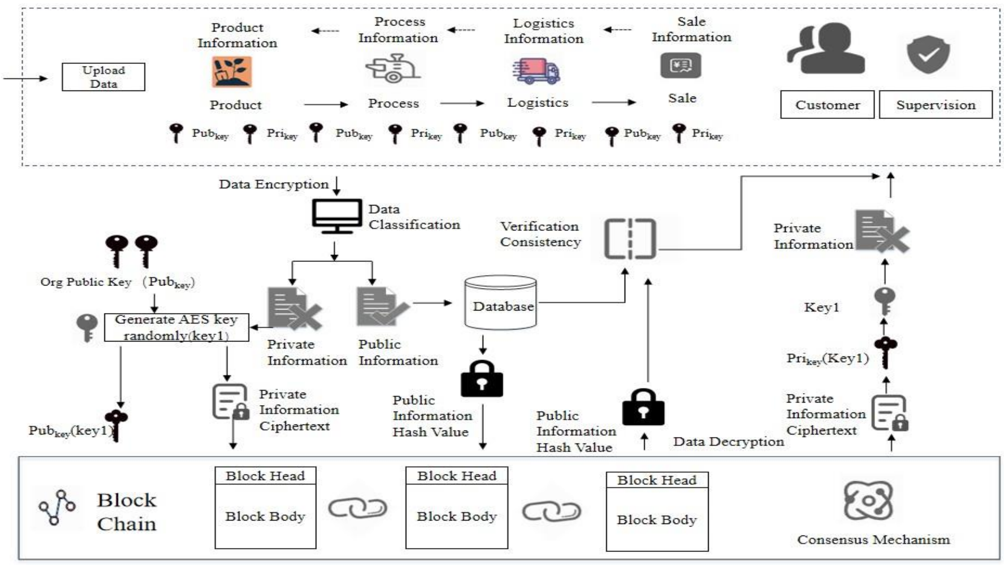

Fig. 5. Data flow diagram depicting traceability information privacy protection [9]

Data Storage - On-Chain as well as Off-Chain: The current storage approach in blockchain traceability systems for agricultural products involves recording the traceability information of each node directly onto the blockchain. As the number of nodes grows, the volume of transaction data increases, leading to escalating storage demands on the blockchain. The blockchain's unique chain-like structure results in low efficiency for data queries; all members of the same blockchain network access the entire data set on the chain ledger.

To address these challenges, this paper proposes an enhanced storage method for the blockchain traceability system specific to agricultural products. This approach utilizes a dual storage mechanism under the 'database + blockchain' model. As illustrated in Fig. 4, once traceability data is uploaded to the system, it is categorized. The public information about the product is stored in a local database, while the encrypted ciphertext and the hash value of this public information are uploaded to the blockchain. In consideration of storage space constraints, the SHA256 algorithm, known for its high efficiency, is used.

The SHA256 algorithm plays a crucial role in the encryption of publicly available information within the blockchain traceability system. This algorithm generates a 64-bit hexadecimal value for any string input of varying length. The structure of the traceability information stored on the blockchain is divided into two parts namely (1) the block head and (2) the block body. The block head primarily comprises key details namely (1) the current block number, (2) the hash value of the previous block, (3) a timestamp, and other relevant details. The block body, on the other hand, encompasses information related to transactions.

In this structure, the term 'Key' refers to the corresponding ID in the 'Value' parameter, serving as both an index and a unique identifier. The 'Value' parameter, which is the actual data written to the blockchain, includes several sub-parameters: 'Type', 'ID', 'PrivateData', and 'InfoHash'. 'Type' denotes the name of the structure body as defined by the 'Value' parameter. 'ID' acts as a unique identifier for the source message record, aligning with the unique ID of the source traceability information in the local database. 'PrivateData' represents the ciphertext of private information, encrypted using the CBC algorithm. Finally, 'InfoHash' is the hash value of the original traceability information, obtained after hashing the data.

Privacy protection process for traceability information: In the supply chain, the data encompasses not only product traceability information but also private data such as transaction details, which are accessible only to relevant companies. Data privacy is a critical concern, especially for competing businesses. This paper proposes a design for protecting the privacy of traceability information. The approach involves encrypting private data using smart contracts before uploading it to the blockchain, along with the hash value of public information. Fig. 5 illustrates this process: transaction data and other private information are encrypted using the Cipher Block Chaining (CBC) mode of the AES encryption algorithm. The necessary encryption key (Key1) is randomly generated by the smart contract and used to encrypt the data before it is uploaded to the blockchain.

To secure Key1, this paper employs Elliptic Curve Cryptography (ECC) for its encryption. The encrypted public key is then assigned to authorize specific viewing nodes. The public key of these authorized nodes, along with the encrypted Key1, forms a key-value pair. This pair is stored in the world state of the smart contract and recorded on the blockchain.

When authorized enterprise nodes need to access the private data on the blockchain, they use their private key to decrypt the Encrypted Key1 on the blockchain. This decryption retrieves the original Key1, which is then used to decrypt and access the private information. This method ensures that private data remains secure and accessible only to authorized parties within the supply chain.

Traceability for anti-counterfeiting process [9]: Fig. 6 illustrates the flowchart of the blockchain traceability system for fruit and vegetable agricultural products. The traceability data is either gathered through Internet of Things (IoT) devices or input manually. Users upload information related to the production, processing, logistics, and sales phases to the system. The system then categorizes this information into private and public data. The private data undergoes CBC encryption before being uploaded to the blockchain, while the public data is stored in a local database. The public information is hashed using the SHA256 algorithm, and the resulting hash value is then stored in the blockchain system, which in turn generates a block number. This block number is updated in the corresponding public information record within the database.

If there is a need to modify the information of the agricultural products, the hash value of the public data has to be re-entered into the blockchain, which updates its block number. Consumers can access the public information and its associated block number by scanning a QR code. They can then hash this public information themselves and use the block number to compare it against the hash value stored on the blockchain. This comparison helps determine whether the product's traceability information has been altered.

7. RESULT- OF IMPLEMENTING BLOCKCHAIN SYSTEM - INITIATIVES OF IMPORTANT BRANDS

Nestlé, Unilever, and Walmart [10,11] are all piloting blockchain-based supply chain solutions for this very reason. Excellent real life example of role of Blockchain for achieving Transparency and Efficiency.

Preventing fraud through transparency: Problems relating to fraud begin and end with data accuracy. Having a completely transparent supply chain that offers accountability at every stage, can and will prevent and reduce food fraud. The advent of specialist food tests that detect any foreign matter in food will mean that such illegal actions can be detected while food is still in the supply chain.

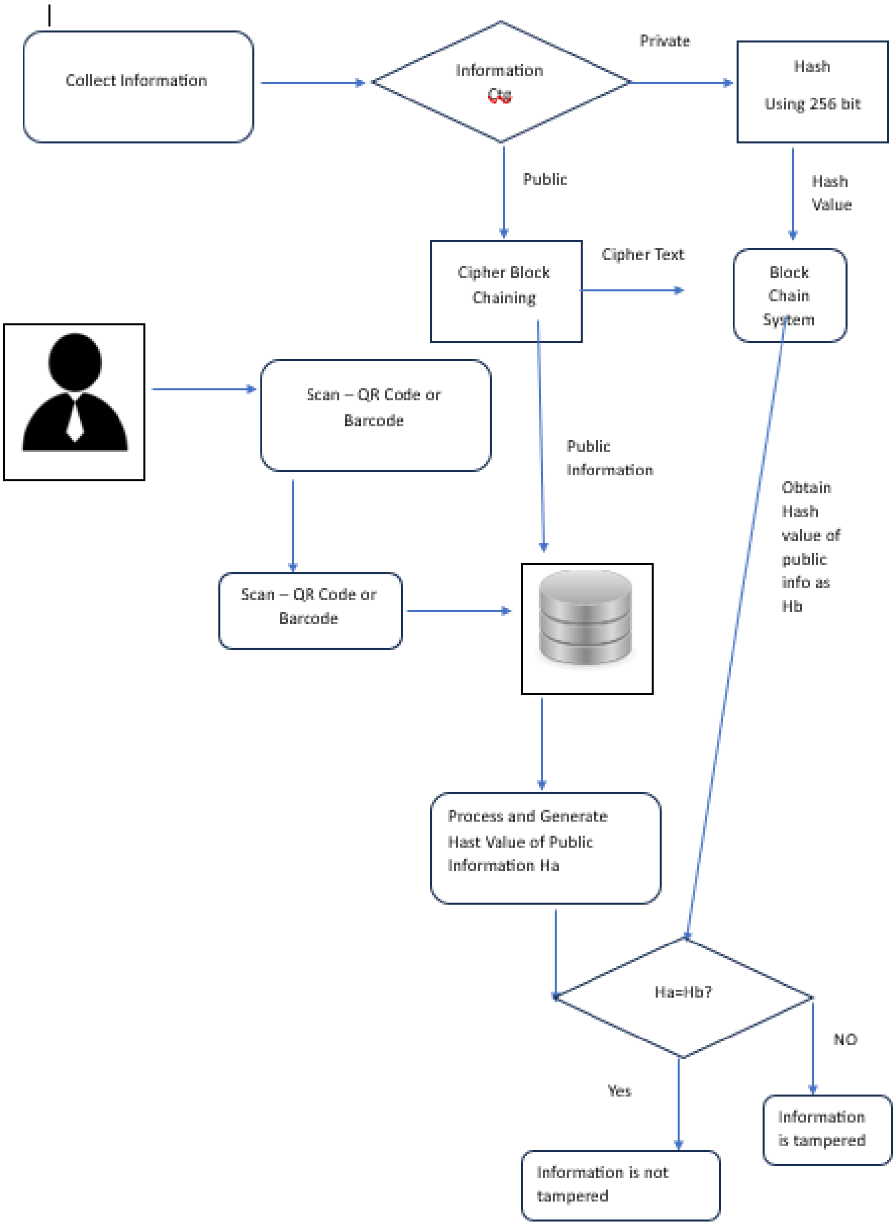

Fig. 6. System traceability flowchart for anti-counterfeiting

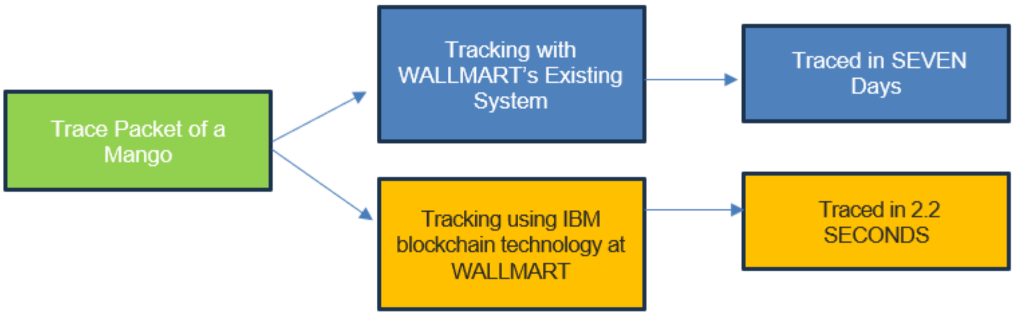

Fig. 7. Packet tracing

Blockchain supply chain solutions could be integrated with smart contracts that would require random tests to be performed at various stages of the supply chain. If produce was found to be not 100% original, the blockchain system would refuse to allow it to continue any further down the supply chain until it had been checked out.

Every individual/company that is involved in the supply chain would have their role recorded in the blockchain. Therefore, if a batch of food was found to have been interfered with, it would only take a matter of seconds to pinpoint the guilty party.

To prevent food fraud using blockchain would be a relatively simple system to put in place. With very little investment, a viable blockchain solution could be easily set up using mostly existing hardware.

Such as system would have prevented the cases of fraud that resulted in the UK's 2013 Horse Meat Scandal and the Halal Meat Turkey Fraud.

Efficiency - speeding up payments throughout the supply chain: Anyone who has ever been part of a supply chain will know that payments are a real frustration at times. Usually, this means allocating staff to creating invoices and chasing down missing payments, etc.

The reason payments take so long is that companies are required to recheck to see that goods have been received before paying invoices. For multinational companies, the sheer volume of paperwork can be overwhelming.

The implementation of smart contracts into food industry supply chain blockchain solutions will allow the automation of payments. Terms and conditions can be pre-programmed into a smart contract meaning that once this set of conditions is satisfied (good delivered and signed for), the smart contract could automatically initiate payment to the sender.

This would, in effect, put an end to the need for a large number of accountants to process invoices, while also reducing errors too.

Blockchain system adoption challenges – technical & non-technical: Although the technology itself is revolutionary, there are many limitations and challenges in its adoption in applications. Considering the length of the article, a short but comprehensive discussion is made on non-technical and technical challenges Blockchain Adoption in Supply Chain.

Challenges - non-technical in nature: The availability of technology does not guarantee its uptake; even now, many warehouses still operate with paper at the integral points, although RFID chips and scanners are now conveniently available, in reach and access. Factors acting against the adoption of technology include the lack of understanding of Blockchain among business leaders, the view that it is a fad, and waiting for wider adoption before committing.

Despite recognizing Blockchain's potential, many business leaders remain reluctant to invest time and money due to the absence of standardized industry practices and norms. For Blockchain to achieve success in the supply chain sector, it's crucial that all key players understand and appreciate its benefits. Convincing these stakeholders of Blockchain's advantages [12] is a significant hurdle in gaining market acceptance.

Another challenge lies in the integration with existing enterprise resource planning (ERP) systems. Most standard ERP systems in use today do not support Blockchain technology, necessitating either the outsourcing of application development specific to a company's supply chain or the establishment of in-house development capabilities. Outsourcing carries risks, including potential privacy breaches, as it involves entrusting sensitive data to third parties. On the other hand, developing in-house solutions lowers privacy risks but requires substantial long-term investment, either in training existing staff or hiring skilled professionals. This can be challenging, given the need for a diverse set of software skills and an understanding of economic, business, and supply chain dynamics.

Beyond these issues, there are other non-technical challenges, often variations or expansions of the ones mentioned. One critical point straddling the technical and non-technical realms is the accuracy of data input into the Blockchain. The data must be correct, as Blockchain's immutable and transparent nature makes it difficult to alter records once entered. If a supply chain partner relies on an unreliable system for recording information, incorporating Blockchain technology might be more harmful than helpful. The immutability feature of Blockchain does not inherently ensure data quality, highlighting the need for reliable data input systems in the supply chain

Challenges – technical in nature: Blockchain, in contrast to conventional databases, exhibits a notably slower performance in both retrieving and recording data. Additionally, it demands substantially more computational power, and scaling these resources effectively is a major challenge. Furthermore, seamless interoperability is essential for all systems that interact with the Blockchain. The payment terms should be brief and adaptable, allowing for easy conversion into any other form of currency, including fiat money. In the subsequent sections, we will delve into these two critical issues in more detail.

Scalability: Scalability refers to a system's capacity to maintain performance and functionality when scaled up to meet increasing user demands. To address scalability challenges, Soohyeong Kim and colleagues have classified scalability methods into five different areas namely (1) on-chain, (2) off-chain, (3) side-chain, (4) child-chain, and (5) inter-chain solutions. In contrast, Junfeng Xie and team have categorized scalability solutions based on transaction volume, block interval time, data storage, and data transmission. We propose a fourfold categorization of scalability solutions: (i) on-chain scalability, (ii) off-chain scalability, (iii) consensus mechanism-based scalability, and (iv) distributed acyclic graph (DAG)-based scalability.

On-chain solutions necessitate structural or fundamental changes to the Blockchain, altering the protocol's core rules. This is technically referred to as a hard fork, or a controversial hard fork in instances where it leads to community division due to disagreements over the update. Examples include sharding, SEGWIT, litecoin, DASH, and Bitcoin Cash.

Off-chain solutions involve secondary protocols built atop the main Blockchain, thus termed second-layer scalability solutions. These solutions transfer transactions off the main Blockchain for private execution between parties, leading to reduced MainNet congestion, increased throughput, lower transaction fees, and space efficiency. Prominent off-chain solutions include RAIDEN, Trinity Network, Plasma Cash, and the Lightning Network.

Consensus Model-based Scalability focuses on optimizing the consensus algorithm to address scalability issues. Solutions in this category include VeChain using Proof of Authority, ARK.io and LISK using Delegated Proof of Stake, Ripple and Stellar using Federated Byzantine Agreement, NEO using Delegated Byzantine Fault Tolerance, and others like Libra, Zilliqa, and Hyperledger.

DAG-Based Scalability, divergent from traditional Blockchain, is a notable form of distributed ledger technology. In this system, transactions are independent and asynchronous, using a topological ordering structure for transaction records. DAG technology does not experience the same scalability issues as Blockchain. Examples in this category include IOTA, Byte ball, NANO, and Hash graph.

Interoperability: While Blockchain adoption is on the rise, the real issue of isolated Blockchains operating in their own 'silos' due to a lack of interoperability standards remains a significant barrier to broader adoption. Addressing the challenges of collaboration and interaction between different types of blockchain namely public blockchain, private blockchain, and consortium blockchains could lead to a more interconnected world. For Blockchain systems to effectively communicate and share certain common features are essential such as consensus models, transaction capabilities, as well as contract functionalities, and standardization. The potential solutions for Blockchain interoperability are generally classified into three categories: (i) Notary Schemes, (ii) Side Chain Relays, and (iii) Hash Locking.

In Notary Schemes, a trusted intermediary or notary is used to verify and confirm the states of interacting Blockchains, thus facilitating operations. An example of this is the Liquid network using Federated Pegged Sidechain as a major solution. The Relay scheme, employed by several interoperability solutions, includes notable examples like Cosmos, Polkadot, and ChainLink.

Hash Locking represents a more practical approach to Blockchain interoperability, though its functionality is somewhat limited. Key solutions in this category include the Inter-ledger Protocol (ILP) and the ARK Core Series. These solutions aim to bridge the gap between different Blockchain systems, enhancing their capacity to work together seamlessly.

8. CONCLUSION

Unlocking the full potential of blockchain technology in the food supply chain relies on widespread adoption by all stakeholders. While blockchain-based traceability and transparency systems offer numerous benefits, including enhanced customer relationships, improved efficiency, and reduced risks, several challenges hinder complete integration.

While blockchain technology holds immense promise for the food supply chain, its implementation remains in its early stages. The industry is still navigating the learning curve, grappling with questions of economic viability and business sustainability. Existing research primarily focuses on technical aspects, neglecting crucial areas like environmental, social, and economic impact. Future studies should consider these factors throughout the development lifecycle of blockchain-based systems. While direct-producer-to-consumer models using blockchain offer increased profitability for producers, the complexity of these systems poses a challenge for less tech-savvy individuals. Furthermore, private and consortium blockchains are favoured over public ones due to scalability and data privacy concerns within the agri-food sector. However, platform selection requires+ careful consideration, as the wrong choice can hinder business performance. Although smart contract development is rapidly evolving, its current pace remains slow, further delaying adoption. The lack of understanding regarding potential applications, economic benefits, and technical intricacies also contributes to hesitant adoption. In-depth research exploring the economic impacts of blockchain integration is critical for addressing this knowledge gap and accelerating adoption.

Significant opportunities exist to enhance supply chains in aspects such as complete traceability, product delivery speed, coordination, and financing. Our studies show that blockchain is an effective solution for overcoming these shortcomings. Supply chain managers who have yet to engage should now evaluate blockchain's applicability to their operations [13,14].

It's crucial for them to participate in creating new guidelines, explore diverse technologies, engage in pilot projects with different blockchain platforms, and collaborate with other companies to develop a supportive ecosystem.

The food supply chain casts a long shadow on our planet, responsible for staggering environmental costs. Agriculture, its cornerstone, demands staggering resources: 17% of global greenhouse gas emissions, 70% of all irrigation water, and a land footprint exceeding 38% of the Earth's surface – more than any other human activity. To meet growing food demands without further burdening the environment, we need a significant shift. The answer lies **in** harnessing the power of digital technology**.**

Agricultural practices account for a significant portion of the food supply chain's carbon footprint, exceeding contributions from processing, packaging, storage, and distribution combined. This raises a crucial question: how can we encourage farmers to adopt more sustainable practices and track their carbon emissions effectively? The answer might lie in privacy-preserving record-keeping systems powered by blockchain technology. Blockchain creates an immutable record of carbon emissions throughout the food production and transportation stages. This transparency fosters trust and accountability among stakeholders, from producers to consumers.

In a technology grounded in blockchain, a Carbon Footprint approach has been suggested to offer insights into the pre-consumption phases of the food lifecycle, encompassing stages from farm to retail. For nations in the developing world, numerous significant challenges exist within their transportation systems. These include the type of transportation used, the availability of vehicles with temperature control, elevated costs associated with transport, and the absence of appropriate infrastructure for storing food. Addressing these challenges is essential for enhancing the efficiency of the food supply chain and for accomplishing the Sustainable Development Goals (SDGs).

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. The 10 Biggest Food Recalls in U.S. History by Garrett Parker Available:https://moneyinc.com/biggest-food-recalls-u-s-history/
2. How Can Blockchain Improve The Food Industry? By Aran Davies Available:https://www.devteam.space/blog/how-can-blockchain-improve-the-food-industry/

3. 12 Blockchain in Supply Chain Case Study in 2024, Cem Dilmegani, AI Multiple Research. Available:https://research.aimultiple.com/blockchain-in-supply-chain-case-study/
4. https://ourworldindata.org/grapher/population-regions-with-projections
5. Building a Transparent Supply Chain Blockchain can enhance trust by efficiency, and speed. by Vishal Gaur and Abhinav Gaiha. Available:https://hbr.org/2020/05/building-a-transparent-supply-chain
6. Top 5 Real-life Blockchain Use Cases in Supply Chain in 2024. Available:https://www.antiersolutions.com/top-5-real-life-blockchain-use-cases-in-supply-chain-in-2023/
7. The Power of Blockchain in Revolutionizing the Food Industry by Tommie van der Bosch, Kim Schneider and Casper Hemelrijk Available:https://www2.deloitte.com/nl/nl/pages/risk/articles/the-power-of-blockchain-in-revolutionising-the-food-industry.html
8. A Trusted Blockchain Based Traceability System for Fruit and Vegetable Agriculture Product by Xinting Yang, Mengqi Li, Huajing Yu, Mingting Wang, Daming Xu And Chuanheng Sun.
9. Impact of Blockchain Technology on Supply Chain Management Efficiency and Transparency in Pakistan, February 2024 in International Journal of Supply Chain Management 9(1):16-26 by Imran Huzaifa Available:https://www.researchgate.net/publication/378387491_Impact_of_Blockchain_Technology_on_Supply_Chain_Management_Efficiency_and_Transparency_in_Pakistan#:~:text=Through%20blockchain%20integration%2C%20supply%20chain,risks%20of%20fraud%20and%20error.
10. Blockchain Enabled Supply Chain Traceability: Enhancing Transparency and Efficiency by By Ajay Kapoor October 2023. Available:https://www.indianchemicalnews.com/opinion/blockchain-enabled-supply-chain-traceability-enhancing-transparency-and-efficiency-19319
11. Transparent Tracking: The Role of Blockchain for Secure & Accurate Supply Chains by ample works November 2023 https://www.amplework.com/blog/role-of-blockchain-in-securing-supply-chains/
12. Blockchain in Supply Chain Management: Enhancing Transparency, Traceability, and Efficiency Digital Skills Ninja June 2023 https://medium.com/@digitalskillsninja/blockchain-in-supply-chain-management-enhancing-transparency-traceability-and-efficiency-53185c342462
13. Blockchain technology for sustainable supply chains: A comprehensive review and future prospects Anil Varma 1, Nalini Dixit 2, Samrat Ray 3, * and Jaspreet Kaur March 2024. Blockchain technology for sustainable supply chains: A comprehensive review and future prospects (researchgate.net)
14. Blockchain in Supply Chain Management: Transforming Transparency and Traceability Prachi Subhedar March 2024.Blockchain in Supply Chain Management: Transforming Transparency and Traceability.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/115611