Review on blockchain technology in food safety and traceability issues

DISCOVERY
SCIENTIFIC SOCIETY

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ABSTRACT

This review explores the potential of blockchain technology to address food safety and traceability challenges within the global food supply chain. Through a comprehensive analysis of existing literature, case studies, and industry developments, the benefits, limitations, and real-world applications of blockchain were examined to enhance food safety and tracking food journeys from farm to fork. The analysis considers the potential for improved transparency, efficiency, and consumer empowerment alongside challenges such as scalability, standardization, and regulatory frameworks. The unique opportunities and considerations for blockchain adoption in regions like Africa were acknowledged. This review provides valuable insights for future research and implementation strategies, aiming to inform stakeholders on how blockchain can contribute to a more secure, transparent, and efficient global food system.

Keywords: Blockchain technology, Food safety, Food traceability, and Africa

1. INTRODUCTION

Food safety and traceability have become paramount concerns in today's globalized food supply chains, driven by increasing incidents of contamination, fraud, and supply chain inefficiencies. Ensuring the safety and integrity of food products from farm to table is essential for safeguarding public health and maintaining consumer trust enhances food safety and traceability very critical concerns in the global food supply chain. Traditional methods often lack data fragmentation, inaccuracy, and lack of transparency. Blockchain technology, with its decentralized and secure ledger system, offers a promising solution for improving food safety and traceability. Blockchain technology has emerged as a promising solution to enhance food safety and traceability by providing transparency, security, and accountability throughout the supply chain (Tapscott and Tapscott, 2016). At its core, blockchain technology utilizes decentralized, immutable ledgers to record transactions or events in a transparent and tamper-proof manner.

Each transaction is cryptographically linked to the previous one, forming a chain of blocks that ensures data integrity and transparency (Mohammed et al., 2023). Key features of blockchain, such as cryptographic seals, decentralized network architecture, and consensus mechanisms, contribute to its effectiveness in addressing food safety and traceability issues (Mohammed et al., 2023). Cryptographic seals ensure the authenticity and integrity of data recorded on the blockchain, while decentralized networks mitigate the risk of single points of failure and enhance transparency (Tapscott and Tapscott, 2016). Consensus mechanisms establish trust and agreement among network participants, further enhancing the security and reliability of the blockchain. Blockchain technology enables real-time visibility into the movement and provenance of food products, enhancing trust, accountability, and efficiency across the entire supply chain.

By recording each step of the production, processing, and distribution process on a distributed ledger, stakeholders can trace the origin, authenticity, and handling conditions of food items with unprecedented accuracy (Mohammed et al., 2023). Various initiatives and pilot projects have demonstrated the feasibility and potential impact of blockchain technology in addressing food safety and traceability issues. From multinational corporations to small-scale farmers and consumers, stakeholders across the food industry are exploring blockchain-based solutions to improve transparency, mitigate risks, and enhance consumer confidence in food products. Despite its promise, implementing blockchain technology in the food industry presents several challenges, including scalability, interoperability, regulatory compliance, and data privacy concerns.

Overcoming these challenges requires collaboration among industry stakeholders, government agencies, and technology providers to develop standards, protocols, and best practices for blockchain adoption in food safety and traceability applications. This review examines how blockchain technology can improve food safety and traceability. It analyses research, case studies, and industry trends to explore the potential benefits, limitations, and real-world applications of blockchain in tracking food from farm to fork. Challenges such as scalability and regulations, while acknowledging opportunities and considerations specific to Africa were explored in this study. The study aims to inform stakeholders and guide future research and implementation of blockchain for a safer and more transparent global food system.

2. LITERATURE REVIEW

Challenges in Food Safety and Traceability

Ensuring food safety and maintaining transparency throughout the complex food supply chain are critical aspects of the global food system. However, several challenges hinder achieving these goals. These challenges were explored in more detail, highlighting the threats they pose to public health and consumer trust, exposing the limitations of traditional food traceability systems, and then how blockchain technology helps eradicate these issues. The production, processing and handling of foods in a hygienic way to safeguard human health is known as food safety. However, with growing international trade of foods increases the challenges to maintain food quality assurance and safety (Patel et al., 2023).

Overview of food safety challenges

Food safety concerns encompass a wide range of issues that can occur at any stage of the food supply chain, from farm to fork. Here is a closer look at some of the most prominent challenges:

Contamination

Foodborne illnesses are a significant public health threat, with contaminated food being a leading cause. Contamination can occur through various means, including:

Microbial contamination: This involves pathogenic bacteria, viruses, and parasites entering the food chain at various points, causing illnesses like E. coli infections and salmonellosis.

Chemical contamination: This can arise from residues of pesticides, fertilizers, environmental pollutants, or improper use of cleaning agents.

Physical contamination: Foreign objects like glass, metal, or plastic can get into food during processing or packaging, posing a physical choking hazard.

Food Fraud

Deliberate adulteration or misrepresentation of food products is a growing concern. This can involve substituting cheaper ingredients, adding unauthorized substances, or falsely labelling products regarding origin or content.

Supply Chain Inefficiencies

Complex and opaque supply chains make it difficult to track food origin and movement. This lack of transparency hinders rapid response during outbreaks and recalls, potentially leading to contaminated products remaining in the market longer. These challenges highlight the vulnerability of the food system and the constant need for vigilance.

Implications of food safety incidents on public health and consumer trust

Food safety incidents can have severe consequences for public health and consumer trust. Here is a closer look at the impact:

Public health risks: Foodborne illnesses can lead to a range of health problems, from mild discomfort to severe illness, hospitalization, and even death. Children, pregnant women, and the elderly are particularly vulnerable.

Economic burden: Foodborne illnesses impose a significant economic burden on healthcare systems, lost productivity, and treatment costs.

Erosion of consumer trust: When food safety incidents occur, consumer trust in the food system suffers. This can lead to decreased consumption of certain food products and a general sense of unease regarding food safety.

The erosion of consumer trust can have a ripple effect throughout the food industry, impacting sales, brand reputation, and overall market stability.

Limitations of traditional food traceability systems

The food traceability system assembles, stores and transmits adequate history of any food products, from cultivation or rearing to the final product in the consumer's basket, at all stages inside the Food Supply Chain (FSC) to check the product for quality control as well as safety and can be traced forward and backward direction whenever required (Aung and Chang, 2014). Traceability is well thought out as a new quality indicator in the food sector. Case-sensitive information storage and handling has become mandatory in the food industry. Food authorities impose regulations to allow monitoring and identification of all raw materials and substances utilized in food product preparation (Dabbene et al., 2014).

These types of necessities have been incorporated by many FSC participants but a number of them still rely on a non-automated paper-based system. The food sector makes use of a traceability system for the enhancement of FSC and facilitates the traceback for food quality and safety (Aung and Chang, 2014). Traditional food traceability systems often rely on paper-based records and manual data entry for record-keeping, but that cannot clear up all the issues. This approach suffers from several limitations that hinder effective food safety management, including:

Lack of transparency: Paper trails can be fragmented and incomplete, making it difficult to track food origin and movement accurately. In the event of a food safety incident, identifying the source of contamination and tracing affected products becomes a laborious and time-consuming process.

Data inconsistency: Manual data entry is prone to errors and inconsistencies, such as typos or missing information. This lack of data integrity can hinder accurate tracing in case of recalls, potentially leading to delays in removing contaminated products from the market.

Slow response times: Paper-based systems are slow and cumbersome. Investigating the source of a food safety incident and issuing recalls can take days or even weeks, allowing contaminated products to remain in the market and posing a risk to consumers.

These limitations of traditional traceability systems highlight the need for more efficient, transparent, secure, and advanced technologies for food safety management. This is where blockchain technology emerges as a potential solution to product quality and supply chain issues.

3. CONCEPT OF BLOCKCHAIN TECHNOLOGY (BCT)

In 1982, David Chaum introduced a cryptographic concept similar to Blockchain technology (Sherman et al., 2019). According to Haber and Stornetta, (1990) which expanded on this idea by describing a method for securely time-stamping digital documents on a chain of blocks. Enhanced this design by incorporating Merkle trees to streamline the process of certifying multiple documents into one block (Patel et al., 2023). The concept of Blockchain Technology (BCT) was conceived in 2008 by an individual or group using the pseudonym Satoshi Nakamoto.

This concept aimed to create a decentralized digital ledger for the cryptocurrency Bitcoin, eliminating the need for trusted central authorities. Over the past decade since Nakamoto's release of the paper "Bitcoin: A Peer-to-Peer Electronic Cash System", Blockchain Technology has become the foundational digital infrastructure for cryptocurrencies like Bitcoin. Blockchain technology has been used to transform many several core traditional industries and its use case in the food supply chain is no exception. By offering a transparent, secure, and decentralized approach to data management, this technology has also shown immense potential to address the issues of food safety and traceability.

The core concept of BCT

At its core, blockchain technology has been used to build trust like no other invention/technology, by functioning as a distributed ledger (a digital record of transactions that is shared and synchronized across a network of computers, or nodes). Below are the fundamental elements of BCT:

Blocks: Imagine a series of chronological pages in a digital record book. Each page, called a block, stores a specific set of data related to a transaction. This data can encompass anything from financial transactions to food origin information, depending on the application.

Nodes: These are individual computers or servers participating in the blockchain network. Each node possesses a complete copy of the blockchain ledger. New information or transactions are validated by a majority of nodes before being added to the chain, ensuring data integrity and preventing unauthorized modifications.

Consensus Mechanisms: This refers to the process by which nodes on the network agree on the validity of a transaction and its subsequent addition to the blockchain. Different consensus mechanisms exist, such as Proof of Work (PoW) and Proof of Stake (PoS), each with its advantages and trade-offs regarding security, speed, and energy consumption (Narayanan et al., 2016).

Decentralized Consensus   Centralized Conser
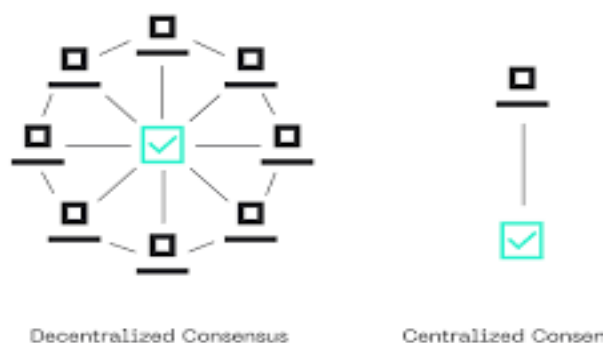
Figure 1 Blockchain Technology with Blocks, Nodes, and Consensus Mechanism
Source: Hacken.io

Blockchain technology is a decentralized ledger system (Figure 1) comprised of digital blocks, connected via cryptographic methods (Giungato et al., 2017). Each block contains data related to a specific transaction, along with virtual signatures to verify its authenticity and links to subsequent blocks, forming the blockchain and making it immutable (Figure 2) (Giungato et al., 2017). Utilizing a hash algorithm, the first block, known as the genesis block, includes essential information such as Hash, Mine difficulty, Nonce, Timestamp, and Merkle tree root records (Nofer et al., 2017).

These blocks are linked together and distributed across all participant computers, forming a peer-to-peer network where participants can verify and add data to blocks simultaneously using a consensus principle. The tamper-proof nature of the data is ensured through the hash algorithm, which generates unique codes for each block, making alterations detectable (Kishigami et al., 2015). The Merkle tree root accumulates hash values for all nodes, further securing the integrity of the blockchain (Nofer et al., 2017).
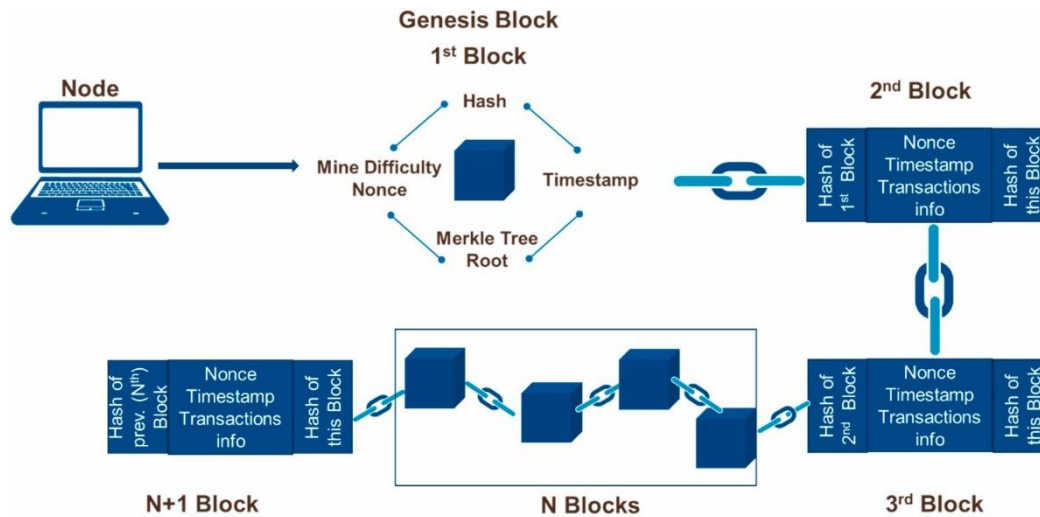
Figure 2 Formation of a Blockchain
Source: Patel et al., (2023)

Here are explanations of the key terms/features used above;

Cryptographic Seals: Every block in a blockchain is cryptographically linked to the previous and subsequent blocks. This creates a chain-like structure where tampering with one block would invalidate the entire chain, making it practically impossible to alter data records without detection.

Decentralization: Unlike traditional systems with a central authority, blockchain operates in a decentralized manner. The distributed ledger eliminates the need for a single point of control, reducing vulnerability to manipulation and increasing network resilience.

Immutability: Once a transaction is added to a blockchain and verified by the network, it becomes immutable. This means the data cannot be altered or deleted, ensuring a permanent and verifiable record of events throughout the food supply chain.

Transparency: All participants on the blockchain network can access the shared ledger, allowing for greater transparency throughout the supply chain. This fosters trust and accountability among stakeholders, from farmers to consumers.

These features, combined, create a secure and transparent environment for recording and tracking any data system. And as make Blockchain technology (BCT) has gained increasing attention from academia and the corporate sector in the postmodern era of globalization, where international interactions and the exchange of goods, services, information, and capital form the basis of all activities. In the food/agricultural sector, the use of data and information has become crucial for productivity and sustainability (Aung and Chang, 2014). As with BCT every step a food product takes, from farm to fork, can be documented and verified on the blockchain, providing crucial insights into its origin, processing methods, and transportation history.

Overview of Blockchain Technology on Food Safety and Traceability Issues

Ensuring food safety and quality in the agriculture production chain requires effective monitoring and efficient food supply chain systems. However, the dynamic nature of information in this chain can pose challenges for tracing (Casado-Vara et al., 2018). As described in our introduction of Blockchain technology (BCT) above, it is clear to be a technology that can effectively provide transparency and immutability in transactions, enhancing stakeholders' trust. It enables traceability in food supply chains, allowing for the tracking of product origins and verification of authenticity (Cai and Zhu, 2016). By storing data in an irreversible and immutable manner, blockchain technology can significantly improve traceability. This facilitates regulatory control and helps identify potential

fraudulent behaviour throughout the supply chain (Liu and Li, 2020). It also prevents the use of false labels in the food market, enhancing compliance with food standards and sustainability practices (Behnke and Janssen, 2020).

The great limitations of traditional food traceability systems can be seen in several food supply chain fraud cases in the past. And all that has paved the way for a need for a better solution to its safety and traceability issue. And blockchain technology presents a promising approach to revolutionizing this. By leveraging its core features of cryptographic seals, decentralization, and immutability, blockchain can enhance trust, transparency, and security within the complex food supply chain. As research and development progress, the integration of blockchain across the food industry holds the potential to create a more secure, transparent, and efficient food system for all stakeholders, from farmers to consumers.

Application of Blockchain in Food Safety and Traceability

The potential of blockchain technology (BCT) in the food system extends far beyond theoretical concepts. Real-world implementations highlight the transformative power of blockchain in enhancing food safety and traceability throughout the food supply chain (Feng, 2016). Below are some of the concrete examples and case studies of how BCT is being utilized to address critical food safety and Traceability.

Walmart's Food Safety Initiative: In a collaborative effort to improve the traceability of pork products, Walmart partnered with IBM to implement a blockchain-based platform in 2017. The system tracks pork from farms in China to stores across the United States. Consumers can scan a QR code on the packaging to access information about the product's origin, processing details, and transportation history (Figure 3). This initiative demonstrates the potential of blockchain for increased transparency and consumer confidence in food safety.

Figure 3 Example of QR code on food packaging
Source: www.uniqode.com

Food Trust's Blockchain Network: Established in 2018, Food Trust is a consortium blockchain platform designed specifically for the food industry. Members include major players like Cargill, Nestle, and Unilever. The platform facilitates secure data sharing and tracking of food products across the supply chain. In a pilot project with McDonalds, Food Trust tracked the journey of romaine lettuce from farm to restaurant, significantly reducing the time needed to identify the source of contamination during a foodborne illness outbreak.

IBM Food Trust & Carrefour's Collaboration: Retail giant Carrefour collaborated with IBM Food Trust in 2018 to track the origin of chicken from Brazil to stores in Europe. Consumers can access detailed information about the product, including farm location, processing details, and transportation data, using a QR code on the packaging. This initiative highlights the potential of blockchain for enhancing transparency for European consumers.

Hyperledger Fabric: In 2017, Jingdong (JD.com), a Chinese e-commerce company, and Kerchin, a beef manufacturer in Inner Mongolia, partnered to launch Hyperledger Fabric, an open-source blockchain platform-based supply chain. With this platform, buyers can access information about the animals used, nutrition, food safety test results, and information related to slaughtering. In the year

2018, a strategy was announced to implement BCT for its meat supply chain, with a major focus on monitoring the Australian cattle supply (Kshetri, 2019).

Alibaba, a Chinese e-commerce behemoth, has launched a trial program to monitor international food consignments sold to China through its online marketplace T-Mall. These consignments were sourced from New Zealand dairy producer Fonterra and Australian healthcare supply company Blackmores (Kshetri and Loukoianova, 2019). This initiative bears similarities to the Hyperledger Fabric system.
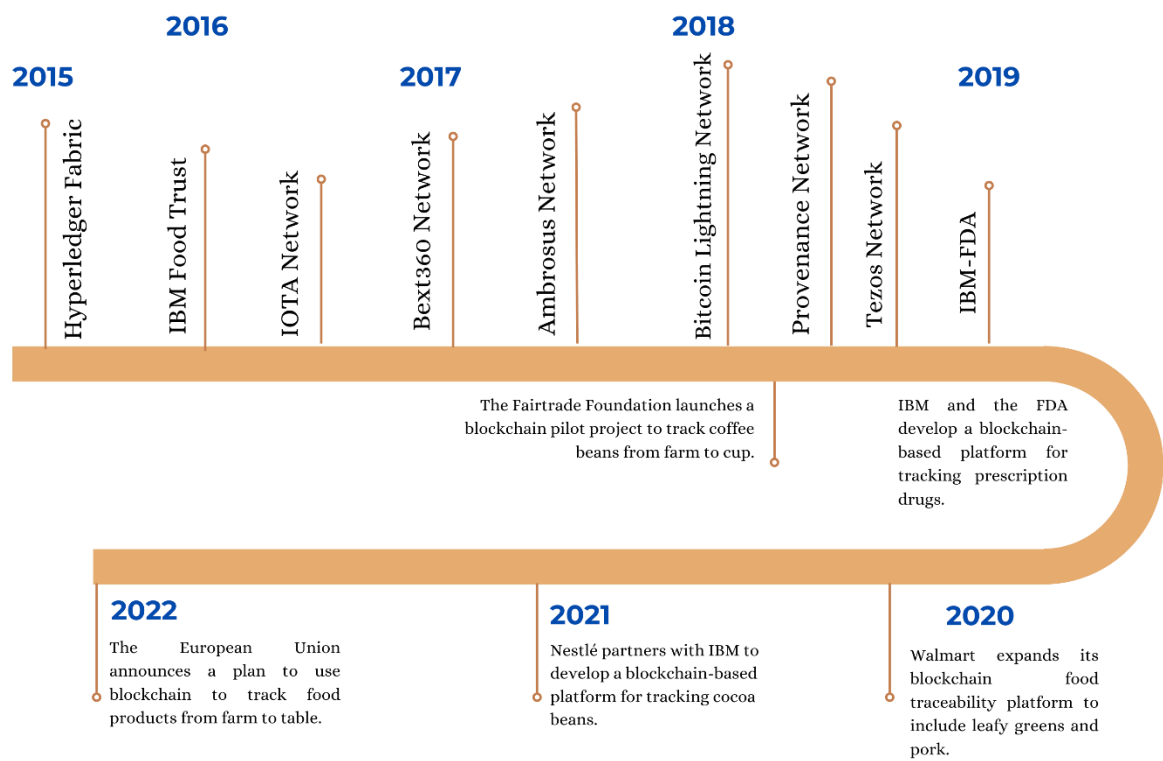
Figure 4 Evolution of Blockchain Technology Application in the Food Supply Chains
Source: George and Al-Ansari, (2023)

Few of the case studies reviewed in past research just as further explained in detail above among many others illustrate how blockchain technology (Figure 4) is being actively implemented by industry leaders to address food safety concerns and improve consumer trust.

Function of Blockchain Technology in Food Safety and Traceability
Blockchain Technology (BCT) has been seen to play various functions in some types of food supply chains, a profound study has been done on the role that BCT plays in a well-functioning diary and livestock supply chain. This is a strategic food supply chain industry but the function of BCT is still not limited to that. As this review study as highlighted in George and Al-Ansari, (2023) on various industries and the specific function of BCT as seen in Table 1 below;

There are some functionalities applicable in food supply just as seen in Table 1, which include but are not limited to Leveraging Blockchain for Provenance Food Tracking, Quality Assurance, and Supply Chain Optimization. This study takes a deeper insight into these, even as blockchain offers a broad functionality for the food supply chain which can be broadly classified into enhancing food safety and traceability across this crucial supply chain. Some of these functionalities this review study dig deeper into are:

Table 1 Blockchain applications across several food Systems

Food Reference	Goal	Advantage	Result
Beef	Quality assurance for consumer's choice	Informed policymaking	Traceability
Halal Food	Trusted information throughout the FSC	Guarantee of food safety and data protection	Reliability
Tea	Steer stakeholder attitudes to adopt sustainable production	Healthy competition	Transparency
Fish	Tracing Shellfish quality	Improve food safety management	Quality
Olive Oil	Tracing food prices while ensuring bi-direction communication between the company and the consumer	Easy integration with existing systems and technologies	Fraud prevention
Rice	Tracing sources and giving credit to farmers	Greater sense of appreciation for farmers	Provenance
Agri-food	Allow quality to be certified	Retailers can justify the sale of "Premium Vegetables"	Better food pricing
Dairy	Create a supply chain void of data silos	Giving privacy to individual stakeholders while also ensuring disclosure of necessary Data	Management
Soybean	Security through transparency and brand imaging	Consumer loyalty	Trust
Sugar	Increase competitiveness	SC resilience	Traceability
Eggs	Ensuring food safety	Improve food safety	Fraud prevention

Source: George and Al-Ansari, (2023)

Provenance Tracking: By recording data at every stage of production and transportation, blockchain enables comprehensive provenance tracking. This allows stakeholders to pinpoint the exact origin of a food product, facilitating targeted recalls during outbreaks and mitigating consumer risk. Additionally, consumers gain valuable insights into the source and journey of their food, empowering informed purchasing decisions.

Quality Assurance: Blockchain can be utilized to record and verify quality control measures throughout the supply chain. This can include data on temperature control during transportation, storage conditions, and adherence to specific quality standards. By creating an auditable record of quality checks, blockchain fosters trust and transparency between producers, distributors, and retailers.

Supply Chain Optimization: The real-time visibility offered by blockchain allows for improved supply chain management. By tracking the movement of food products efficiently, bottlenecks and inefficiencies can be identified and addressed. This can lead to faster delivery times, reduced food waste, and overall cost optimization within the food supply chain (Feng, 2016).

These functionalities highlight the versatility of blockchain technology in addressing various aspects of food safety and traceability.

Blockchain Integrations useful in Food Safety and Traceability

Blockchain technology has immense potential to enhance food safety and traceability by integrating with other emerging solutions. This integrated approach creates a connected ecosystem that benefits stakeholders across the food supply chain (Figure 5). By combining blockchain with technologies like the Internet of Things (IoT), Smart Contracts, and Data Analytics for Enhanced Traceability, real-time data on factors like temperature, and location can be collected from sensors embedded in packaging and

vehicles. This data is securely stored on the blockchain, enabling stakeholders to identify issues and maintain optimal food quality throughout the supply chain. This integration exemplifies how blockchain enhances efficiency and control in the food system.
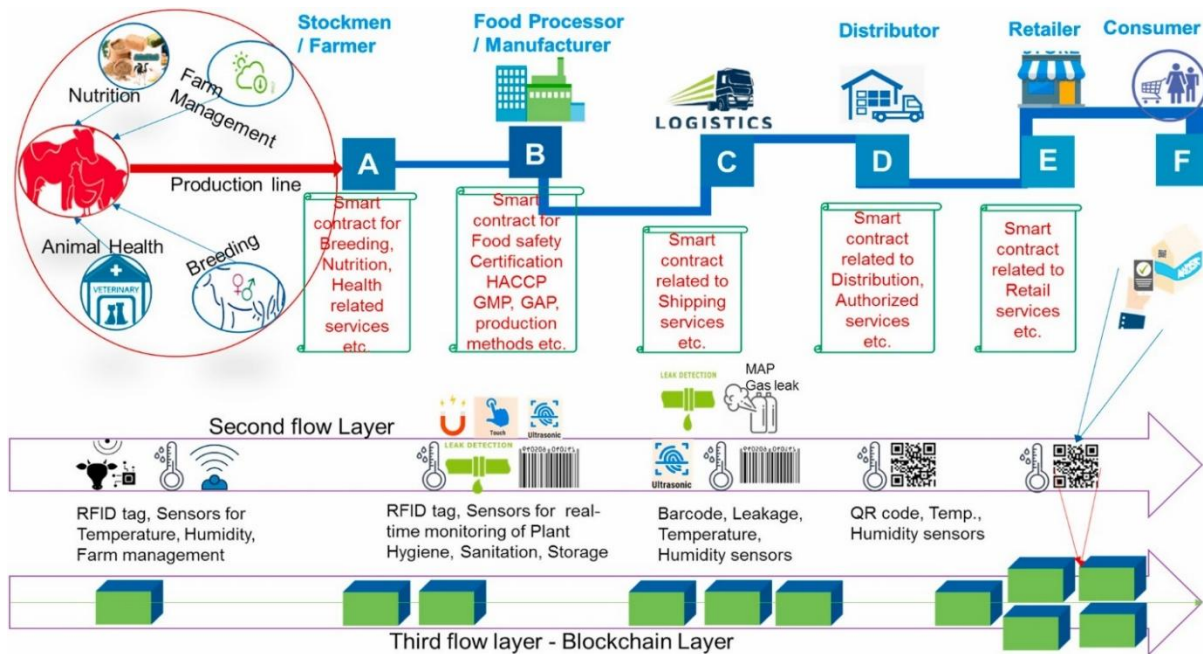
**Figure 5** Blockchain technology-driven food traceability.
Source: Patel et al., (2023)

The potential of blockchain is further amplified when integrated with other emerging technologies:

Internet of Things (IoT): Sensors embedded in packaging, storage facilities, and vehicles can collect real-time data on factors like temperature, humidity, and location (Figure 6). This data can be securely stored on the blockchain, providing a comprehensive record of the product's condition throughout the supply chain. This integration offers valuable insights for ensuring optimal food quality and timely identification of potential issues (Leme et al., 2020).

Smart Contracts: These self-executing contracts can automate specific actions within the food supply chain based on predefined parameters stored on the blockchain. For instance, a smart contract can trigger an automatic recall if temperature sensors detect a breach in safe storage conditions. This automation can expedite response times during outbreaks and minimize product contamination risks (Lu et al., 2021).

Data Analytics: The vast amount of data generated throughout the food supply chain can be analysed using advanced algorithms. This can help identify patterns, predict potential contamination risks, and implement preventive measures. By integrating blockchain with data analytics, stakeholders can gain deeper insights into food safety trends and proactively address potential issues (Leme et al., 2020).

The combined power of blockchain, IoT, smart contracts, and data analytics presents a future-oriented approach to food safety and an efficient food system that prioritizes consumer safety and well-being.
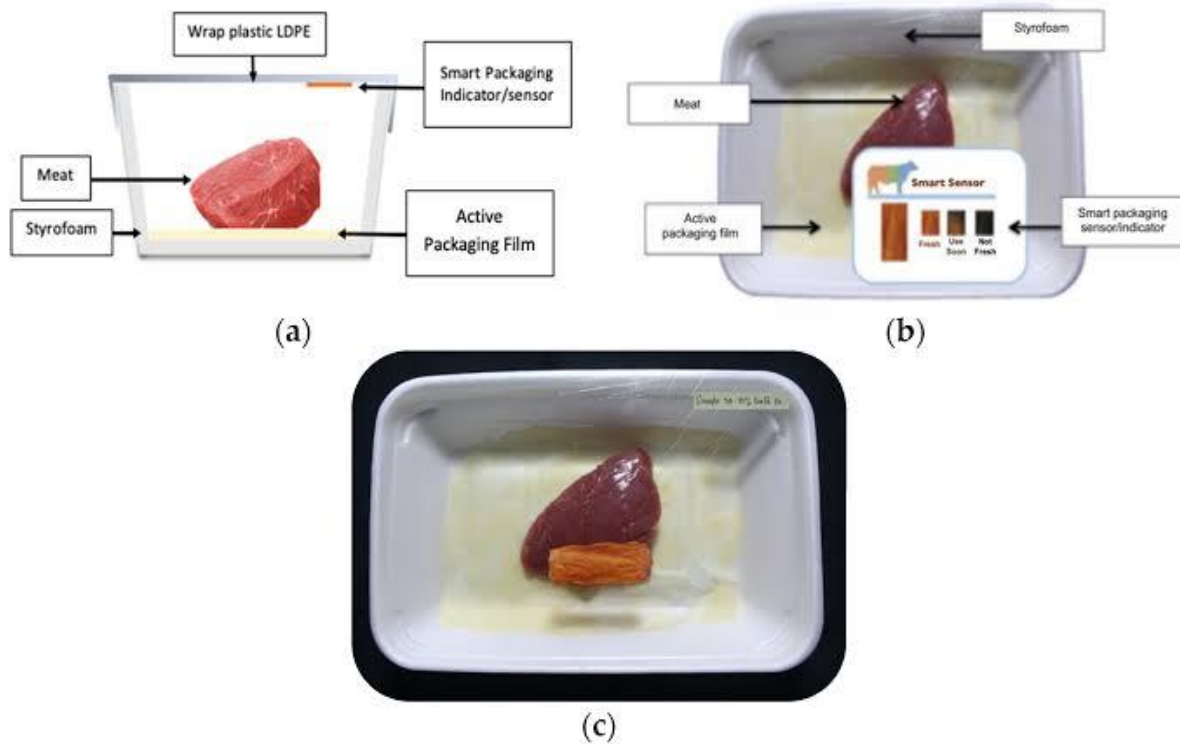
Figure 6 Sensor on food packaging

Source: Andi et al., (2022)

(a) Design of the intelligent and active packaging system; (b) Prototype of the intelligent packaging; and (c) Its application on fresh beef

The Potential of Blockchain in Food Safety and Traceability

As research and development efforts continue, and successful implementations become more widespread, it is expected that blockchain technology will play an increasingly prominent role in the future of food safety and traceability, especially in developing continents like Africa (James, 2023). The regulations and standards are perceived as essential and not particularly strict. Nevertheless, traceability's responsibility was primarily determined to fall upon the shoulders of cooperatives and retailers. While having international standards like the GS1 standard was most familiar to participants, knowledge of major parts of the continent and also had limited traceability laws. All of which can slow down the potential of BCT being applicable in food safety and traceability on the continent. Here are some of the potentials this review study found that a crucial to the future directions of blockchain applicability:

Standardization and Interoperability: Currently, there is a lack of standardized protocols and data formats across the food industry, hindering the seamless integration of different blockchain platforms. Collaborative efforts to establish industry-wide standards will be crucial for fostering greater interoperability and efficient data exchange between various blockchain systems (James, 2023).

Integration with Artificial Intelligence (AI): AI algorithms can analyse the vast amount of data stored on the blockchain, identifying patterns and trends that may be undetectable by humans. This can enable proactive risk prediction and preventive measures to be taken before food safety issues arise.

Consumer Engagement and Education: As blockchain technology becomes more integrated into the food supply chain, consumer awareness and education will be critical. Developing user-friendly interfaces and mobile app-based solutions can encourage broader participation and empower consumers to make informed choices based on the information accessible through blockchain platforms (James, 2023).

Regulatory Frameworks and Governance: As blockchain adoption within the food industry continues to evolve, clear and well-defined regulatory frameworks will be necessary. These frameworks should address issues like data privacy, security standards, and compliance requirements to ensure responsible and ethical implementation of the technology (Sengupta and Kim, 2021).

By addressing these considerations and fostering collaboration across stakeholders, blockchain technology has the potential to revolutionize food safety and traceability practices, creating a more transparent, secure, and efficient food system for all participants, from farmers to consumers.

Benefits and Challenges of Blockchain Adoption in Food Safety

Food safety is a paramount concern for consumers worldwide. Traditional tracking methods often rely on paper-based records, which are susceptible to errors and manipulation. Blockchain technology presents a revolutionary approach to enhancing transparency, traceability, and overall food safety within the supply chain. However, like any emerging technology, blockchain adoption faces its own set of challenges and barriers. This section will explore both the potential benefits and obstacles associated with implementing blockchain in the food industry.

Potential benefits of blockchain in improving food safety

It was evidenced in the study of Patel et al., (2023) (Figure 7), blockchain offers a multitude of advantages that can significantly improve food safety practices:

Enhanced Transparency: This has been seen in this review studies several times as one of the most significant benefits of blockchain is its inherent transparency. As explained in the early part of the work blockchain operates on a distributed ledger, meaning all participants in the network share a secure and tamper-proof record of transactions. This allows consumers and stakeholders to access critical information about a food product's journey, from farm to fork. Imagine scanning a QR code on a package of chicken and instantly seeing its origin farm, processing details, transportation history, and even storage temperatures. This level of transparency empowers consumers to make informed choices about the food they purchase and fosters trust within the food system.

Improved Traceability: Blockchain technology excels at facilitating comprehensive traceability throughout the supply chain. Every step a food product takes can be recorded on the blockchain, creating an immutable audit trail. This allows for pinpoint identification of a product's origin in the event of a foodborne illness outbreak. For instance, during a romaine lettuce contamination scare, a blockchain-based platform enabled swift identification of the source farm, minimizing product recalls and consumer risk.

Streamlined Efficiency: Blockchain can significantly improve efficiency within the food supply chain. Real-time data visibility allows for better inventory management, identification of bottlenecks, and optimization of the supply chain. This translates to faster delivery times, reduced food waste, and overall cost savings for producers and retailers.

Empowered Consumers: By providing access to detailed information about the food they consume, blockchain empowers consumers. Imagine knowing the ethical sourcing practices behind your coffee beans or the sustainable farming methods used for your vegetables. This newfound knowledge allows consumers to make purchasing decisions aligned with their values and support responsible agricultural practices.

Food Quality Assurance: Blockchain can be utilized to record and verify quality control measures throughout the supply chain. Data on factors like temperature control during transportation, storage conditions, and adherence to specific quality standards can be securely stored on the blockchain. This creates an auditable record that fosters trust and transparency between producers, distributors, and retailers.

Challenges and barriers to blockchain adoption

Despite its immense potential, widespread adoption of blockchain technology in the food industry faces several challenges:

Scalability: Current blockchain platforms may struggle to handle the massive amount of data generated within a global food supply chain. As the technology matures and scalability solutions are implemented, this challenge will be gradually addressed.

Standardization and Interoperability: The lack of standardized protocols and data formats across the food industry hinders the seamless integration of different blockchain platforms. Collaborative efforts to establish industry-wide standards are crucial for fostering greater interoperability and efficient data exchange between various blockchain systems.

Regulatory Uncertainty: The regulatory landscape surrounding blockchain technology is still evolving, particularly regarding data privacy, security standards, and compliance requirements. Clear and well-defined regulatory frameworks are essential for ensuring responsible and ethical implementation of the technology.
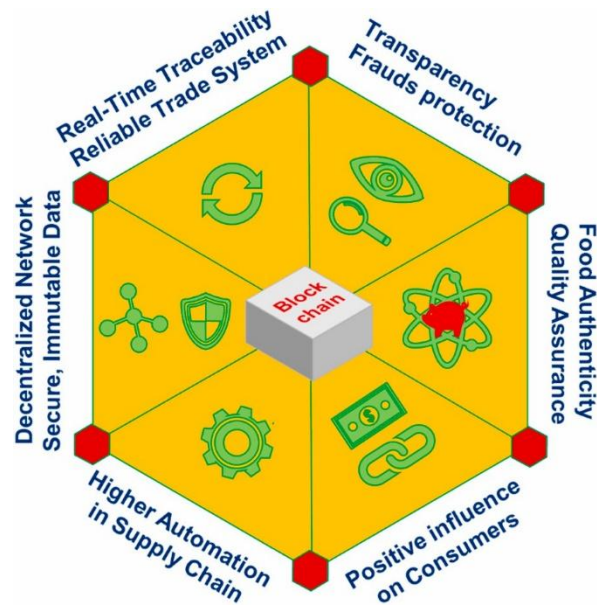
Figure 7 Benefits of Blockchain technology in food safety and traceability
Source: Patel et al., (2023)

Cost and Investment: Developing and implementing blockchain-based solutions can be a significant financial investment for food businesses, particularly for small and medium-sized enterprises (SMEs). Cost-effective solutions and government incentives can encourage broader adoption across the industry.

Technical Expertise: Successfully implementing and maintaining blockchain systems requires technical expertise. Capacity-building initiatives and training programs are essential to equip stakeholders across the food supply chain with the necessary skills to utilize this technology effectively.

Incorporating blockchain technology into agriculture holds promise, but it is also intricate and demands diverse expertise for successful implementation (James, 2023). It entails rethinking the current infrastructure to ensure all stakeholders in the food supply chain are aligned. The growing use of digital technologies like blockchain poses challenges for various actors in the economy and society, requiring them to adjust accordingly. Policymakers in agriculture must prioritize aspects such as traceability, transparency, and facilitating farmers' access to credit.

Strategies for Overcoming Challenges and Maximizing the Benefits of Blockchain Technology
Despite these challenges, these are strategies from several of the above review literature to overcome them and unlock the full potential of blockchain for effective traceability and a safer food supply chain:
Collaborative Efforts: Collaboration between industry leaders, government agencies, technology providers, and NGOs is crucial for developing and implementing pilot projects that highlight the value proposition of blockchain in the food industry.
Investment in Infrastructure: Targeted investments in improving internet connectivity, particularly in rural areas, will be crucial for facilitating wider adoption of blockchain technology across the agricultural sector.
Standardization Initiatives: Industry-wide collaboration is essential to establish standardized protocols and data formats for seamless data exchange between different blockchain platforms.
Developing User-Friendly Solutions: Focusing on user-friendly interfaces and mobile app-based solutions can encourage broader participation among both consumers and smaller food businesses with limited technological resources.
Promoting Education and Awareness: Educational initiatives and awareness campaigns can help stakeholders across the food supply chain understand the benefits and applications of blockchain technology. This can encourage broader acceptance and investment in blockchain-based solutions.

Government Incentives: Government incentives, such as tax breaks or grants, can encourage food businesses, particularly SMEs, to invest in implementing blockchain technology.

Continuous Research and Development: Ongoing research and development efforts are crucial for improving the scalability, security, and interoperability of blockchain platforms. Additionally, exploring the integration of blockchain with other emerging technologies like artificial intelligence (AI) and the Internet of Things (IoT) holds immense promise for further enhancing food safety and traceability.

By implementing these strategies and fostering a collaborative environment, the challenges associated with blockchain adoption can be overcome, thereby unlocking its transformative potential for creating a more secure, transparent, and efficient food system that prioritizes consumer safety and well-being.

The African Context of Blockchain Adoption in Food Safety and Traceability (Opportunity and Challenges)

Africa presents a unique landscape for blockchain adoption in food safety. The continent's high mobile phone penetration (over 1.3 billion users in 2023), creates a foundation for mobile app-based traceability solutions. Furthermore, limited existing infrastructure, often reliant on paper records makes blockchain's secure and transparent data management particularly attractive. For smallholder farmers, dominant in Africa's agriculture, blockchain offers the potential for verified provenance and access to premium markets seeking ethical sourcing (James, 2021). However, challenges remain. Unclear regulations, limited technical expertise, and patchy internet connectivity in rural areas require solutions. Capacity-building initiatives and exploring offline data collection methods are crucial for ensuring inclusive participation by all stakeholders in the African food system.

The implementation of Blockchain technology in the African food supply chain has huge potential to bring significant benefits to all stakeholders involved. Especially as the market is highly fragmented and plagued with Middlemen. This technology gives the farmer the ability to easily track and verify their products' origin and quality can increase their crops' value and marketability (Astill et al., 2019). For retailers and consumers, the Blockchain's transparency and traceability can help ensure the product's safety and quality (Casado-Vara et al., 2018). Additionally, smart contracts and digital payments can streamline financial transactions, reducing the costs and risks associated with traditional payment and transfer of ownership (Casado-Vara et al., 2018).

4. CONCLUSION AND RECOMMENDATIONS

This study explored how blockchain technology can solve the issue of food safety and traceability within the global food system. Blockchain technology offers significant advantages for food safety, including transparency, traceability, efficiency, and consumer empowerment. Though issues like scalability, standardization, and regulations exist, particularly in developing economies like Africa. However, pilot projects are already demonstrating the positive impact of blockchain. As research progresses and implementation strategies are refined, blockchain has the potential to revolutionize the global food supply chain and ensure food safety for future generations. However, successful implementation relies on widespread adoption and participation from all stakeholders.

The importance of blockchain in addressing food safety concerns cannot be overstated. Traditional traceability methods often lack transparency and are susceptible to manipulation. Blockchain, with its immutable record-keeping capabilities, empowers stakeholders to identify potential issues and ensure food quality throughout the supply chain. This is particularly relevant in Africa, where fragmented supply chains and limited resources pose significant challenges to food safety. The future of the food industry is undoubtedly brighter with blockchain integration. Imagine a world where consumers in New York can scan a QR code on their mangoes and instantly see their journey from a farm in Mali, complete with details on sustainable farming practices and proper post-harvest handling.

This level of transparency fosters trust and empowers consumers to make informed choices. The African continent is still with its progress in leveraging blockchain for food safety. Pilot projects in countries in East Africa are exploring the technology's potential to track land use, and agricultural produce, improve market access for smallholder farmers, and ultimately enhance food security, as noted by (James, 2023). And by further harnessing the power of blockchain, a more secure, transparent and equitable food system can be created for all, with Africa playing a significant role in shaping this future. As a continent with a huge food supply chain, it boosts 60% of global cultivatable land.

Recommendations

Blockchain in food safety

As of the time of making this review study, we are currently in a world with a high buzz of Artificial Intelligence (AI) and as much as we have highlighted in the Article about the role it plays in BCT implementation, one cannot stop but think maybe this technology is only a bubble as BCT was the household technology of around 2020 into 2021. But ignoring trends the applicability of this technology to solve age-long cannot be over and the potential of blockchain technology to revolutionize food safety and traceability in particular continues to evolve. Even as more future use cases and adoption spreads, below we examine emerging trends, key recommendations, and the broader implications for stakeholders within the food system.

Integration with IoT and AI

The integration of blockchain with the Internet of Things (IoT) holds immense promise. Sensors embedded in packaging, storage facilities, and vehicles can collect real-time data on temperature, humidity, and spoilage markers. This data can be securely stored on the blockchain, providing an immutable record for stakeholders to monitor product conditions and identify potential issues. Furthermore, artificial intelligence (AI) can analyse the vast amount of data generated throughout the food supply chain, identifying patterns and predicting potential contamination risks, enabling proactive preventive measures.

Standardization and interoperability

Industry-wide collaboration is crucial for establishing standardized protocols and data formats. This will foster the seamless integration of different blockchain platforms across the food supply chain, facilitating efficient data exchange and creating a more interconnected ecosystem.

Consumer engagement

As blockchain adoption progresses, user-friendly interfaces and mobile app-based solutions can encourage broader consumer participation. Imagine scanning a QR code on a food product and instantly accessing its origin, processing details, and even its sustainability footprint. This level of transparency empowers consumers to make informed choices aligned with their values.

Suggestion for Further Studies

Collaborative Research and Development: Continued research and development efforts focused on improving the scalability, security, and interoperability of blockchain platforms are essential. Additionally, exploring the integration of blockchain with AI and IoT holds immense potential for enhancing food safety.

Government and Industry Collaboration: Collaborative efforts between government agencies, industry leaders, technology providers, and NGOs are crucial for establishing clear and well-defined regulatory frameworks that promote responsible and ethical implementation of blockchain technology in the food sector.

Developing User-Friendly Solutions: Focusing on user-friendly interfaces and mobile app-based solutions can encourage broader participation among both consumers and smaller food businesses with limited technological resources.

Standardization Initiatives: Developing standardized protocols and data formats is essential for fostering seamless data exchange between different blockchain platforms. Industry-wide collaboration with a focus on standardization will be crucial for creating a more interconnected food system.

Policy Implications

Industry Stakeholders: Food producers, distributors, and retailers can leverage blockchain to enhance transparency, build consumer trust, and improve supply chain efficiency. This translates to potential cost savings, reduced food waste, and a stronger brand reputation.

Policymakers: Governments can play a crucial role in promoting blockchain adoption by creating a supportive regulatory environment, investing in infrastructure development, and providing incentives for businesses, particularly SMEs, to implement blockchain solutions.

Consumers: Blockchain empowers consumers by providing greater transparency and traceability information about the food they purchase. This allows consumers to make informed choices based on their values and supports sustainable agricultural practices.

By following these recommendations and fostering collaboration across stakeholders, the full potential of blockchain technology can be unlocked to create a more secure, transparent, and efficient food system that prioritizes consumer safety and well-being for future generations.

Informed consent
Not applicable.

Ethical approval
Not applicable.

Conflict of Interest
The author declares that there are no conflicts of interests.

Data and materials availability
All data associated with this study are present in the paper.

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