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The role of blockchain technology in promoting adequate services: Case of food traceability

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Abstract

Blockchain technology has emerged as a transformative solution in various sectors, particularly in enhancing food traceability. While there is substantial theoretical discussion surrounding blockchain technology, empirical studies that specifically evaluate its effectiveness in food traceability are still scarce. Most existing research focuses on the potential of blockchain without providing concrete evidence from real-world applications. This study explores the role of blockchain in promoting adequate services within the food supply chain, focusing on its ability to increase transparency, accountability, and efficiency. By providing a decentralised and immutable ledger, blockchain facilitates real-time tracking of food products from farm to retailer, ensuring that consumers have access to accurate information regarding the origin and route of their food. Case studies illustrate how blockchain can mitigate issues such as food fraud, contamination, and inefficiencies, ultimately fostering trust among stakeholders. "The analysis reveals that blockchain technology enables rapid identification of contamination sources.", thus enhancing food safety and reducing health risks. The findings highlight the potential of blockchain not only to enhance food safety and quality but also to empower consumers and improve regulatory compliance. This study underscores the importance of adopting blockchain technology in the food industry as a means to promote adequate services and ensure a safer food supply.

Keywords: Blockchain; Food supply chain; Traceability; Consumer Trust; Food safety; Internet of Things; Food Tracking

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1. Introduction

In recent years, blockchain technology has garnered substantial attention across various sectors, especially in enhancing supply chain management. This innovative technology, considered by its decentralised and immutable nature, offers a promising solution to longstanding issues related to transparency and accountability. This capability not only addresses longstanding issues related to food safety and quality but also fosters consumer confidence and trust by ensuring that information about sourcing and handling is readily accessible. Hinton and Mahbod (2019:25) define blockchain technology as a decentralised system that uses a distributed ledger to record transactions among network participants in real-time. In the context of the food industry, blockchain's potential is especially vital, as consumers increasingly demand assurances regarding the safety and quality of their food. This study examines the role of blockchain technology in promoting adequate services, with a particular focus on food traceability. This study claimed that the significance of blockchain in food traceability extends beyond mere tracking; it fundamentally reshapes how stakeholders interact and share information (David et al., 2022:10). Walmart collaborated with IBM to develop the IBM Food Trust blockchain platform, aimed at enhancing food traceability. This initiative allows Walmart to track the origin of food products within seconds, significantly reducing the time needed to trace back contaminated products during food safety incidents. For example, in a 2018 mango contamination case, Walmart was able to trace the source of the issue in just 2.2 seconds, compared to the previous process, which took nearly a week. This rapid response capability demonstrates how blockchain fosters collaboration among stakeholders and improves overall food safety.

Traditional traceability methods often involve cumbersome processes that can delay responses to food safety incidents. In contrast, blockchain enables real-time data sharing among all participants in the supply chain, from producers to retailers. The study found that this capability not only streamlines operations but also enhances the ability to quickly identify and respond to potential hazards, thereby safeguarding public health and minimising economic losses (Wang et al., 2020:111). In an era marked by increasing concerns over foodborne illnesses and the ethical sourcing of products, the application of blockchain in food traceability offers a promising solution. Blockchain streamlines these processes, allowing for real-time data sharing and rapid identification of potential risks (Happy et al., 2023:630). As the demand for transparency in the food supply chain grows, understanding the role of blockchain technology in promoting adequate services becomes essential for stakeholders looking to enhance food safety and improve overall service delivery.

The study sought to answer the following question: In what ways can blockchain technology promote traceability in food products? After answering this question, the study found that food traceability is vital for ensuring transparency and preventing food fraud within our food supply chain. The rise of blockchain technology offers a hopeful chance to transform the way document information is monitored in a decentralised and secure way, improving food traceability. To answer the question and achieve the aim, the study was structured as follows. While the first section is an introduction, the second section explained the concept of food traceability, its characteristics and challenges. The third section explained traditional method food traceability systems. The fourth section explained the significance of traceability within food supply chains. The fifth explained the applicability of blockchain technology to food traceability. The section also discussed the challenges that may hinder the successful adoption of blockchain technology in food traceability. The last section consisted of a conclusion and proffered recommendations for future studies.

2. The concept of food traceability

Food production, processing, distribution, consumption, and disposal involve a variety of components and procedures, which contribute to the complexity of the food system (Pereira et al. 2020). Ensuring openness, accountability, and sustainability across the whole food supply chain is difficult due to these interrelated activities. Addressing these issues and enhancing the food supply chain's sustainability depend heavily on food traceability. According to Zhou et al. (2022), traceability strategies can reduce the use of pesticides, enhance management techniques, standardize farming operations, and promote environmental preservation. It is crucial to comprehend what "traceability" is and how it functions in food systems to completely recognize the significance of food traceability. Olsen and Borit (2013), defines traceability as the capacity to monitor the origin, distribution, location, and use of goods, components, materials, or services.

Food traceability is a fundamental paradigm in contemporary food systems, enabling the comprehensive tracking of food products and their components across the entire supply network, encompassing all stages from initial production or harvesting to the point of consumption (Oh et al., 2025). This intricate process is essential for ensuring accountability and transparency, allowing stakeholders to monitor the provenance, processing methods, and distribution pathways of food items (Ellahi et al., 2023). The inherent complexity within agri-food supply networks, attributable to the extensive network of stakeholders across agriculture, processing, distribution, and retail, poses a substantial challenge to establishing resilient and transparent traceability frameworks (Demestichas et al., 2020). Food traceability is a critical component of modern supply chains, ensuring that products can be tracked from their origin to the consumers. Understanding the fundamental principles of food traceability sets the stage for exploring the various drivers that necessitate its implementation.

2.1. Drivers for food traceability

Food traceability has become increasingly important due to rising consumer demand for transparency and safety in the food supply chain. Understanding the key drivers behind food traceability sets the stage for exploring innovative solutions that enhance this process.

As the food industry faces increasing pressure from various stakeholders, it is essential to identify the key drivers that compel businesses to adopt traceability systems. These drivers not only highlight the challenges within the industry but also pave the way for innovative solutions, such as blockchain technology, to enhance traceability efforts. Vu et al. (2023:508) contributed a multi-layered model to guide Blockchain adoption in food supply chains, addressing adoption drivers, barriers, and applications. Their model offered a structured approach for practitioners in navigating the complexities of Blockchain integration. Srivastava and Dashora (2022:3438) built on this by providing a focused analysis of Blockchain applications in agrifood supply chains, proposing solutions for scalability and privacy challenges and enhancing food safety and traceability.

Rocha et al. (2021:95) believes that traceability systems can provide various advantages to companies. Traceability system, with integral part of quality control operation can contribute to the increased raw materials, better production efficiency and warehouse-inventory. More efficient distribution systems and consequently, less recall costs plus greater sales for products lacking detailed information about their attributes (Rocha et al. 2021:95). Factors for a mandatory food traceability can perhaps be identified based on regulatory and safety/quality, as well as social (customer attitudes and demands) economic or technological

considerations (Bosona and Gebresenbet, 2023). Implementation of food traceability system in accordance with standards & regulations act as a major driver for the industry. Food traceability regulations are often established by government due to political pressure after food safety incidents for ensuring the quality and integrity of their own food. When the food traceability system required by law and market, most of food companies start to adapt into it (Bosona and Gebresenbet, 2023).

The European Union and the United States are key actors in the promotion of food traceability measures. Examples of regulatory requirements legislation include the General Food Law in the EU and the Food Safety Modernization Act in the United States (FDA, 2011:111). Many countries do not have specific legislation regarding food traceability. Charlebois et al. (2014:1104) conducted a study on the policies and requirements for food traceability in twenty-one nations and discovered that a significant percentage of countries lack exact food traceability laws.

In addition to regulatory pressures, food safety concerns are a critical driver for traceability. The ability to quickly identify and respond to foodborne illness outbreaks is essential for minimizing risks to consumers. The regulatory requirements imposed by governments and international bodies such as the EU law no. 178, which mandates traceability in the food supply chain, have been instrumental in promoting the adoption of traceability systems (Regattieri et al., 2007). These regulations are designed to ensure that food products can be traced back to their origin, thereby facilitating the recall of unsafe products and ensuring compliance with safety standards (Opara and Mazaud, 2001:239). The regulatory framework not only protects consumers but also helps in maintaining the integrity of the food supply chain (Islam and Cullen, 2021).

2.2. Safety and quality value

Food safety and quality are significant elements in the food sector that are receiving more focus because of several instances of food contamination. Food traceability is now crucial because of the risks of foodborne illnesses, as well as food fraud and concerns regarding sustainable production practices, such as labour conditions (Rejeb and Rejeb, 2020:35). Safety and quality are central motivators for the adoption and advancement of food traceability systems across the global food supply chain. Traceability enables rapid identification and removal of unsafe or poor-quality products, minimizing risks to consumers and reducing the likelihood of costly recalls and reputational damage for companies (Hall and Johnson-Hall, 2021). Consumers increasingly view food safety and quality as interconnected, and their demand for transparency has made traceability a key policy and market requirement (Van Rijswijk and Frewer, 2008). Effective traceability systems not only help ensure compliance with food safety regulations but also build consumer confidence by providing assurance of product authenticity and quality (Qian et al., 2020).

Technological innovations, such as blockchain and smart sensors, further enhance the ability to monitor and verify food quality parameters throughout the supply chain, supporting data-driven decision-making and improving overall food safety outcomes (Gallo et al., 2021). Ultimately, the value placed on safety and quality by consumers, regulators, and industry stakeholders drives continuous investment in and implementation of robust traceability systems to protect public health and maintain trust in the food system (Hall and Johnson-Hall, 2021).

Abass et al. (2024:276) found that traceability does not have a direct effect on production systems for enhancing food safety but serves to gather data on product characteristics and processes along the supply

chain. Although Pathogen Reduction (PR) and Hazard Analysis and Critical Control Point (HACCP) systems have a more direct impact on food safety, traceability systems can help facilitate contractual agreements between supply chain firms to enhance food safety (Abass et al., 2024:276). Logistics operations are crucial in agribusiness due to the brief life cycle of food products. Continuous examining and traceability throughout the supply chain are essential to maintain food quality and safety as many food products deteriorate during transportation (Rejeb and Rejeb 2020:35).

2.3. Social

According to Rejeb and Rejeb (2020::36) consumers' increasing trust in their food, society's rising health consciousness, higher incomes, and evolving lifestyles drive food firms to adopt traceability methods. Although companies value maintaining a positive image, retailers are the main influencers advancing food traceability techniques or systems (Heyder et al., 2012:102). Nevertheless, the writers highlight that retailers have heavily invested in their own brands and consequently require safeguards against consumer trust being eroded by food emergencies. It is important to note that the social aspect can also negatively impact companies' attempts to distinguish themselves through traceability. Rocha et al. (2021:95) suggest that the possibility of being associated with food safety issues and negative publicity may motivate a company to stay unidentified, regardless of their strong safety track record. Additionally, consumers are sceptical of producers' claims due to the potential for deception, further diminishing the perceived value relative to the cost (Rocha et al. 2021:95).

The development of food traceability systems is motivated by various social implications that are linked to safety and quality. Globalisation has led to an uptick in consumer desire for a broader range of foods, causing the global food chain to get longer and more intricate, making local issues turn into worldwide crises swiftly (WHO 2017). The World Health Organisation reports that approximately 600 million individuals, which is nearly 1 out of every 10 people globally, become sick due to consuming contaminated food and 420,000 of them perish annually (WHO 2017). The organisation emphasises that consumers need to be aware of the food they consume by reading labels on packaging, making informed decisions, and understanding common food risks. An increased understanding among the general public regarding food safety concerns may prompt numerous producers to implement more accurate traceability measures (Ellahi et al., 2024:8944.).

2.4. Consumer demand and confidence

Consumer concerns about food safety, animal welfare, and environmental impact have intensified the demand for transparency in food production and handling. Traceability systems address these concerns by providing detailed information about the origin and handling of food products, thereby enhancing consumer confidence (Bitzios et al., 2017). Country-of-origin labeling and food fraud prevention are also significant drivers from a consumer perspective (Bitzios et al., 2017).

2.5. Technological

Technological advancements play a crucial role in driving a new wave of traceability applications (Salampasis et al., 2012:302). Liu et al. (2024:60) believe that more advanced devices and systems are needed to establish

efficient traceability systems, but their high costs deter food companies from investing in them. Nonetheless, newer, more efficient, and cost-friendly food traceability technologies are being developed, allowing traceability data to be incorporated in various stages of the supply chain (Liu et al., 2024:60). In general, Information Technology is crucial for improving the efficiency of record storage and data retrieval, which is vital for traceability.

3. Traditional method food traceability systems

Traditional food traceability systems have long been a cornerstone in ensuring food safety and quality, particularly in the transportation and processing of perishable goods. These systems primarily rely on manual record-keeping and adherence to good hygiene practices. Despite their widespread use, traditional methods face significant challenges, particularly in terms of efficiency and cost-effectiveness. For instance, while they are less expensive to implement than modern systems, they often result in higher losses due to inefficiencies in tracking and responding to food safety issues (Bakare, 2018:20). The susceptibility of agricultural products to contamination during transportation underscores the need for effective traceability mechanisms to prevent food-borne illnesses, which affect millions annually (Bakare, 2018:19).

In the context of processed foods, traditional traceability systems encounter unique challenges due to the complexity of the food supply chain. The variety of raw materials and the transformations they undergo during processing complicate traceability efforts. Traditional methods, such as physical separation and batch definition, are often inadequate for the intricate processes involved in food manufacturing. As a result, there is a growing interest in integrating novel technologies like isotope analysis and DNA tracking to enhance traceability in processed foods (Qian et al., 2020:679). These methods offer more precise tracking capabilities, although they are not without their own set of challenges and limitations.

The limitations of traditional traceability systems are further highlighted by their inability to effectively manage data visibility and prevent tampering. Traditional systems often suffer from issues such as data invisibility and the risk of sensitive information disclosure, which can undermine consumer trust and safety (Qian et al., 2020:683). The reliance on manual record-keeping poses significant challenges in terms of accuracy and completeness. Human error is a common issue, with mistakes in data entry or record maintenance leading to discrepancies in traceability information. Additionally, the lack of standardisation in documentation practices across different regions and sectors can further exacerbate these inaccuracies. This variability makes it increasingly difficult to ensure that all stakeholders in the supply chain are operating under the same standards (Jabbar et al., 2024). In contrast, modern technologies like blockchain offer promising solutions by providing secure, transparent, and tamper-proof records. However, the transition from traditional to modern systems is often hindered by the high costs and complexity associated with implementing new technologies (Qian et al., 2020:683).

Traditional food traceability systems, like documenting the product's journey through the supply chain on study, are insufficient to satisfy customer needs and foster trust. These systems' shortcomings include a lack of transparency, inaccurate data recording, challenges in tracking the product's journey, and the possibility of losing or damaging the documents (Aung and Chang 2014). Traditional food traceability procedures, such

study-based documentation, for example, are prone to being lost or damaged, and assistance is required to guarantee the accuracy of the data.

Despite these challenges, traditional traceability systems continue to play a vital role in the food industry, particularly in regions where modern technologies are not yet feasible. They provide a basic framework for ensuring food safety and quality, albeit with limitations in efficiency and accuracy. The ongoing development of hybrid systems that combine traditional methods with modern technologies, such as RFID and blockchain, offers a potential pathway for improving traceability without completely overhauling existing systems (Badia-Melis et al., 2015:393). These hybrid approaches aim to leverage the strengths of both traditional and modern systems to enhance overall traceability performance.

The evolution of food traceability systems is also driven by the need to address consumer demands for transparency and accountability in the food supply chain. Traditional systems, while foundational, often fall short in providing the level of detail and immediacy that consumers now expect. This has led to increased interest in smart traceability solutions that integrate digital technologies like IoT and cloud computing to provide real-time data and insights (Yu et al., 2022:910). These advancements not only improve traceability but also enhance food safety and consumer confidence by enabling more proactive and informed decision-making.

3.1. Food traceability: current challenges

Food traceability is essential for ensuring the safety, quality, and integrity of food products throughout the supply chain. However, several challenges hinder effective traceability systems. While blockchain technology offers significant advantages in enhancing food supply chain traceability, it is essential to acknowledge the challenges that may impede its widespread adoption. High implementation costs, resistance to change among stakeholders, and data security concerns are notable obstacles that require careful consideration.

3.2. High implementation costs

The financial investment in food traceability encompasses expenses related to infrastructure development, system maintenance, and personnel training. These costs can be prohibitive, especially for small and medium-sized enterprises within the agri-food sector. Smaller producers may find it particularly challenging to bear these costs, which could lead to a fragmented implementation across the supply chain. For instance, Boutros et al. (2019) highlights that in school foodservice operations, the high cost of implementing advanced traceability systems is a major challenge, alongside issues like unexpected food substitutions by vendors.

Despite these challenges, the importance of food traceability cannot be overstated. Effective traceability systems enhance consumer confidence by providing verifiable information about food origins, processing methods, and safety practices. As consumers become increasingly conscious of their food choices, they demand transparency regarding sourcing and production. This growing expectation for accountability not only benefits consumers but also encourages producers to maintain higher safety and quality standards (Jabbar et al., 2024). Ultimately, addressing the current challenges in food traceability is crucial for building a more resilient and trustworthy food supply chain.

4. The significance of traceability within food supply chains

Having established the applicability of blockchain in enhancing food traceability, the study delves into the broader significance of traceability in food supply chains. Understanding its importance not only underscores the value of implementing such systems but also highlights the potential for improved food safety, consumer trust, and overall market efficiency. Traceability within food supply chains is a critical component for ensuring food safety and quality, as well as for maintaining consumer confidence. The implementation of effective traceability systems allows for the rapid identification and management of food safety incidents, thereby minimizing the distribution of unsafe or poor-quality products (Aung and Chang, 2014:172). This capability is particularly important in the context of food safety scandals, where traceability can help mitigate the negative impacts on public perception and reduce the potential for costly recalls (Aung and Chang, 2014:172). Moreover, traceability systems provide a mechanism for verifying the authenticity and quality of food products, which is increasingly demanded by consumers (Aung and Chang, 2014:172).

However, the implementation of traceability systems is not without challenges. It requires substantial investment and coordination among supply chain members, which can be a barrier for some organizations (Dash et al., 2022). Cost-sharing mechanisms have been proposed as a solution to distribute the financial burden of implementing traceability systems more equitably among supply chain partners (Dash et al., 2022). Additionally, the complexity of modern food supply chains, with their numerous participants and fragmented networks, poses significant challenges to the development of effective traceability mechanisms. Despite these challenges, the benefits of traceability, such as improved food safety and reduced food waste, make it a worthwhile investment for many organizations (Dong et al., 2023:1513).

Despite the clear benefits, the implementation of traceability systems in food supply chains requires substantial investment and coordination among supply chain members. The cost-sharing models have been proposed as a viable solution to distribute the financial burden of implementing these systems, making it more feasible for all members involved (Dash et al., 2022). Additionally, certification and smart contracts have been identified as effective tools to address information asymmetry and ensure that suppliers with high-level traceability are preferred, thus promoting higher standards of food safety (Haleem et al., 2019;'335). These mechanisms not only incentivize investment in traceability systems but also help in maintaining a high level of food safety and quality across the supply chain.

Traceability is a vital element in modern food supply chains, offering significant benefits in terms of safety, quality, and consumer confidence. The integration of advanced technologies like blockchain has further strengthened traceability systems, making them more robust and reliable. However, the successful implementation of these systems requires strategic investment and collaboration among supply chain members, supported by innovative solutions such as cost-sharing and certification. As the food industry continues to evolve, the importance of traceability will only grow, necessitating ongoing research and development to address emerging challenges and opportunities.

4.1. Benefits and opportunities of food traceability

Food traceability has emerged as a crucial component in ensuring food safety and quality, offering numerous benefits and opportunities for the food industry. The integration of smart technologies into traceability systems has significantly enhanced the ability to monitor and manage food safety across global supply chains.

For instance, smart traceability systems, which incorporate portable detection devices, smart indicators, and sensors, have shown to improve food safety by providing real-time data and insights into the food supply chain (Yu et al., 2022:905). These systems not only help in preventing food safety incidents but also restore consumer confidence by ensuring transparency and accountability in food production and distribution.

Feng et al. (2020) posits that the adoption of blockchain technology in food traceability systems has further revolutionized the industry by providing enhanced security and transparency. Blockchain's decentralized nature allows for the secure recording and sharing of transaction information, making it easier for consumers to track the origins of food products. This technology addresses the limitations of traditional IoT systems, which often rely on centralized paradigms that can obscure transaction details. By implementing blockchain-based traceability systems, the food industry can improve food safety management and sustainability, offering a robust solution to traceability concerns (Feng et al., 2020).

Food traceability systems offer significant benefits across the supply chain. Qian et al. (2020) state that food traceability enhances food safety by enabling rapid identification and removal of contaminated products, thus reducing the scale and impact of food recalls and protecting public health. These systems also improve supply chain transparency, allowing consumers and stakeholders to access detailed information about food origins, processing, and handling, which builds trust and meets growing demands for transparency (Verna et al., 2025). Additionally, traceability systems support better quality management and process control, leading to improved operational efficiency and reduced food waste by saving uncontaminated food from unnecessary disposal (Dong et al., 2023). The integration of advanced technologies such as blockchain, IoT, and AI further strengthens data security, accuracy, and real-time monitoring, contributing to more sustainable and resilient food supply chains (Verna et al., 2025).

5. Applicability of blockchain technology to food traceability

The integration of blockchain technology offers promising applications within food traceability systems. To fully appreciate its impact, it is fundamental to explore specific use cases and benefits that demonstrate how blockchain can improve traceability across the food supply chain. As the study explores the applications of blockchain, it is essential to consider how this technology addresses the previously discussed drivers for food traceability. In the rapidly evolving global food supply chain, the need for transparency, efficiency, and traceability has become increasingly paramount. Blockchain technology holds immense potential to address these challenges, revolutionising the way food traceability is managed. (Kshetri and DeFranco, 2020:106). Blockchain's inherent characteristics of transparency, traceability, and real-time tracking of products, data, owners, and actions can significantly enhance supply chain performance. (Difrancesco et al., 2023:620).

The applicability of blockchain technology in food traceability has garnered significant attention as the food industry grapples with increasing demands for transparency, safety, and efficiency. This capability is particularly crucial in an era where foodborne illnesses and fraud can have serious implications for public health and consumer trust. Blockchain technology presents a compelling solution for enhancing food traceability systems due to its inherent characteristics of immutability, transparency, and decentralization. These core attributes of blockchain technology offer a pathway to improve food safety, enhance supplier reputation, increase the visibility of small farmers, and improve efficiency in tracing food contamination sources (Kshetri and DeFranco, 2020).

Within the intricate domain of agri-food supply networks, blockchain technology presents a disruptive innovation poised to revolutionize food traceability, offering advanced mechanisms to surmount conventional obstacles and establish resilient, streamlined tracking infrastructures (Demestichas et al., 2020). The rise of blockchain technology is one possible way to overcome the difficulties associated with conventional traceability (Garaus and Treiblmaier, 2021). Blockchain technology, in contrast to the data structure of traditional food traceability technology, offers a decentralized system that can collect data from all food chain participants without the need for a central entity (Xu et al., 2020). Blockchain technology, when used in conjunction with a distributed ledger system, can assist guarantee data security and authenticity while offering thorough traceability throughout the food supply chain (Wang et al., 2020).

Additionally, blockchain enhances accountability among all participants in the food supply chain. With each transaction recorded on a decentralised ledger, stakeholders can verify the authenticity of food products and their associated claims. For instance, consumers can trace organic or sustainably sourced products back to their origin, ensuring that their purchasing decisions align with their values. This level of transparency fosters trusts between consumers and brands, ultimately driving consumer loyalty and encouraging ethical consumption practices (Jabbar et al., 2024). The integration of blockchain into existing food traceability systems also offers the potential for cost savings and increased efficiency. By streamlining processes and reducing the need for intermediaries, blockchain can lower administrative costs associated with tracking and documenting food items.

Moreover, smart contracts in blockchain technology could be widely used to oversee food supply chains to tackle various issues concerning food safety and traceability. The notable benefits of incorporating blockchain technology with smart contracts in the food sector tracing system encompass data compatibility, auditability, transparency, cost savings, product tracking, legitimacy, and trustworthiness (Casino et al., 2021:10). The adoption of digital technologies, such as blockchain, has significantly enhanced the traceability capabilities within food supply chains. These technologies facilitate the secure and transparent recording of product information, which can be accessed by all stakeholders in the supply chain (Wang et al., 2022). For instance, blockchain technology has been applied to agricultural food supply chains to improve data security and reduce the risk of fraud (Wang et al., 2022). By enabling the tracking of food products from farm to table, these technologies help ensure that food safety standards are met and that consumers can trust the products they purchase (Wang et al., 2022).

5.1. Integration of blockchain in food traceability

Addressing the challenges in food traceability is crucial for the successful implementation of blockchain technology in the food supply chain. Strategies such as developing cost-effective solutions, fostering stakeholder education and collaboration, and establishing robust data governance frameworks can facilitate overcoming these obstacles, leading to a more transparent and efficient food supply chain. Blockchain technology is increasingly being recognized as a innovative tool for enhancing food traceability systems. The integration of blockchain with other technologies such as the Internet of Things and Radio Frequency Identification offers promising solutions to the challenges faced by traditional traceability systems.

The amalgamation of blockchain technology emerges as a transformative solution to surmount these challenges, offering a decentralized, immutable, and transparent ledger system capable of capturing and

securely sharing critical data pertaining to food products at each stage of the supply chain (Antonucci et al., 2019). Blockchain's inherent architecture, characterized by its distributed and robust nature, is well-suited for global financial systems, but its applicability extends seamlessly to supply chain tracking, contracts, and various operational domains. Blockchain technology's integration into food traceability systems represents a significant advancement, promising enhanced transparency, security, and efficiency across the supply chain, addressing critical challenges related to data integrity and consumer trust (Jarka, 2019).

The integration of blockchain with other digital technologies is transforming the food supply chain by improving management, automation, and sustainability. Blockchain's ability to provide a transparent and traceable system aligns with the goals of Industry 4.0 and Web 3.0, offering potential synergies that enhance the efficiency and sustainability of food supply chains4. Moreover, blockchain's role in achieving the United Nations Sustainable Development Goals (SDGs) by improving food safety and reducing environmental impact is being explored (Chandan et al., 2023).

With a clear understanding of the drivers behind food traceability, the study can examine how blockchain technology serves as a transformative solution to these challenges. By integrating blockchain into existing traceability frameworks, the food industry can address issues related to transparency, accountability, and efficiency. The integration of blockchain technology in food traceability has become a promising solution to address the challenges arising from the increasing worries about food safety and the complexity of modern supply chains. The strategic incorporation of blockchain technology into food supply ecosystems instigates a foundational reorganization, fostering unprecedented levels of traceability, transparency, and data integrity, explicitly designed to mitigate the persistent and complex issues inherent in food safety management, quality assurance frameworks, and the streamlined efficiency of supply networks (Ellahi et al., 2023).

Employing blockchain technology provides an innovative framework for resolving the complex problems inherent in modern food supply networks, offering a notable prospect to revolutionize food traceability practices and reinforce consumer reliability. The fundamental architecture of blockchain, characterized by its decentralized and immutable ledger system, enables the creation and maintenance of a comprehensive and secure record that meticulously documents each discrete stage within the food supply chain (Ellahi et al., 2023).

Moreover, the integration of blockchain can foster greater consumer trust and engagement. With the increasing demand for transparency regarding food sourcing and safety, consumers are more likely to support brands that provide verifiable information about their products. By incorporating features such as QR codes linked to blockchain records, consumers can easily access detailed information about the history of their food, including its origin, processing methods, and transportation conditions. This level of transparency not only empowers consumers but also encourages ethical consumption practices (Jabbar et al., 2024).

5.2. Characteristics of blockchain-based traceability

Blockchain-based traceability systems provide a range of distinctive characteristics that enhance the tracking and verification of products throughout the supply chain. These characteristics address many limitations of traditional traceability methods, offering a more secure and efficient framework for managing product information.

5.2.1. Decentralised and trust-less network

Bosona and Gebresenbet (2023:33) state that blockchain consists of numerous nodes that come together to create a peer-to-peer network. There is no central equipment or management system in place. The system's excellent robustness means that the whole system's function will not be impacted by the destruction or loss of any node. The participants share the data, and they have the ability to verify the data using digital signature technology, eliminating the necessity of a centralised authority and reliance on mutual trust.

5.2.2. Smart contracts in the traceability operations within a business process

Smart contracts, a key feature of blockchain, further enhance traceability by automating and enforcing agreements between supply chain participants, such as verifying compliance with safety standards or triggering alerts if quality parameters are breached (Tan et al., 2022). These contracts can prevent data tampering and unauthorized information disclosure, ensuring that only validated and authorized transactions are recorded and shared among stakeholders (Lin et al., 2019). By integrating blockchain and smart contracts, food traceability systems can achieve greater efficiency, accountability, and trust, enabling rapid identification of issues and improving overall food safety and quality assurance (Creydt and Fischer, 2019). Moreover, smart contracts paired with IoT devices can prevent parties from creating incorrect records.

5.2.3. Consensus mechanism

According to Tian et al. (2024:4812) the consensus mechanism is how all blockchain participants agree on the record's validity. A computer system utilises a cryptographic proof to accomplish this task. The consensus mechanism helps to prevent manipulation of data in the traceability process.

5.2.4. Transaction transparency and anonymity of the traceability chain

Participants with access to the blockchain network have clear and open visibility into the rules and information regarding its operation (Ølnes et al., 2017:356). Every node can see every transaction, and every node remains unidentified. As a result, it can guarantee the traceability, dependability, safety, and timely information of agricultural products, as well as achieve transparent management throughout the entire process from harvesting to sales.

5.2.5. Tamper-proof and traceable data

Tamper-proof and traceable data are critical components of food traceability systems, particularly when leveraging blockchain technology. Each member of the supply chain will have transaction details saved in the block, while by nature, the data is tamperproof and nonerasable (Xu et al., 2019:399). Hence, communication tasks can be investigated and monitored. The operational tasks-such as audit checks, logging of operations, tracking of logistics, and many other tasks-are done in a very reliable method with transparent data management. By creating a tamper-proof record of each step in the supply chain, blockchain-based traceability systems can help to build consumer trust and ensure the authenticity of food products, especially for organic and premium items. According to Xu et al. (2019:399) several studies have highlighted the potential of blockchain to address many of the food safety challenges facing the industry today, such as the ability to quickly

identify and isolate the source of contamination in the event of a food safety incident. Another trend in food traceability is the increasing use of sensors and the Internet of Things to gather real-time data about food products throughout the supply chain.

5.2.6. High reliability of systems and data

Blockchain technology allows every node within a blockchain network to access full data through decentralised data storage. All nodes collectively maintain the data. Changes made to the database on just one node are considered invalid unless over 51% of nodes in the entire supply chain are under control (Lin et al., 2017:50).

5.3. Blockchain-driven food traceability: enhancing transparency and accountability in the food supply chain

The modern food supply chain has become increasingly complex, with products often traversing multiple stages and locations before reaching the consumer. This complexity can make it challenging to trace the origin and journey of a particular food item, which is crucial for ensuring food safety and quality. (Dabbene et al., 2014:65). Blockchain technology has appeared as a promising solution to address these traceability challenges (Duan et al., 2020:1784). The trustworthiness, precision, and openness of blockchain technology make it appealing for managing supply chains. Blockchain has the ability to improve the transparency and responsibility of the food supply chain by establishing a decentralised, unchangeable ledger of transactions. (Kshetri and DeFranco 2020:109). This is especially important in the food sector, where being able to identify the origin of contamination or quality problems is crucial for managing risks and ensuring consumer safety (Duan et al., 2020:1784).

One of the key benefits of blockchain in the food supply chain is its ability to enhance traceability. By integrating blockchain with technologies like the Ethereum Virtual Machine (EVM) and (IoT) sensors, the entire journey of a product can be securely documented in an unalterable digital ledge (Adewusi et al., 2023:479). This integration not only rejuvenates consumer confidence and product authenticity but also lays the groundwork for robust sustainability and toxicity assessments. The use of real-time IoT sensors ensures that variables crucial to product quality are continuously monitored, addressing the industry's challenges related to foodborne diseases and substantial food wastage (Sunny et al., 2020).

The process of blockchain-enabled food traceability can be illustrated as a three-layer system (Figure 1) in which the physical flow layer shows the movement of food items from producer to consumer in the tangible food supply chain. The second level of flow includes a digital system that captures data from the physical layer through sensors, RFID, QR codes, and other digital technologies at the same time. In the third layer of the digital blockchain infrastructure network, data is verified by all participants through a smart contract and consensus algorithm, generating virtual data blocks at each supply chain step. This digital layer also syncs up with the physical layer and generates a series of data blocks. If someone attempts to hack or modify data, the hash value of the block in question will be altered, preventing the changed data from being added to the blockchain, making it a platform for permanent record-keeping. The food item undergoes different stages of production before reaching the consumer's shopping cart, with data being logged onto the blockchain at every stage.

The integration of blockchain technology also fosters greater collaboration among supply chain stakeholders. By providing a shared platform for recording and accessing data, blockchain encourages more effective communication and information sharing. This collaborative environment enables stakeholders to work together to identify and address potential risks proactively. According to Datta et al. (2023), enhanced collaboration through blockchain can lead to improved operational efficiency, reduced waste, and a more resilient supply chain overall.

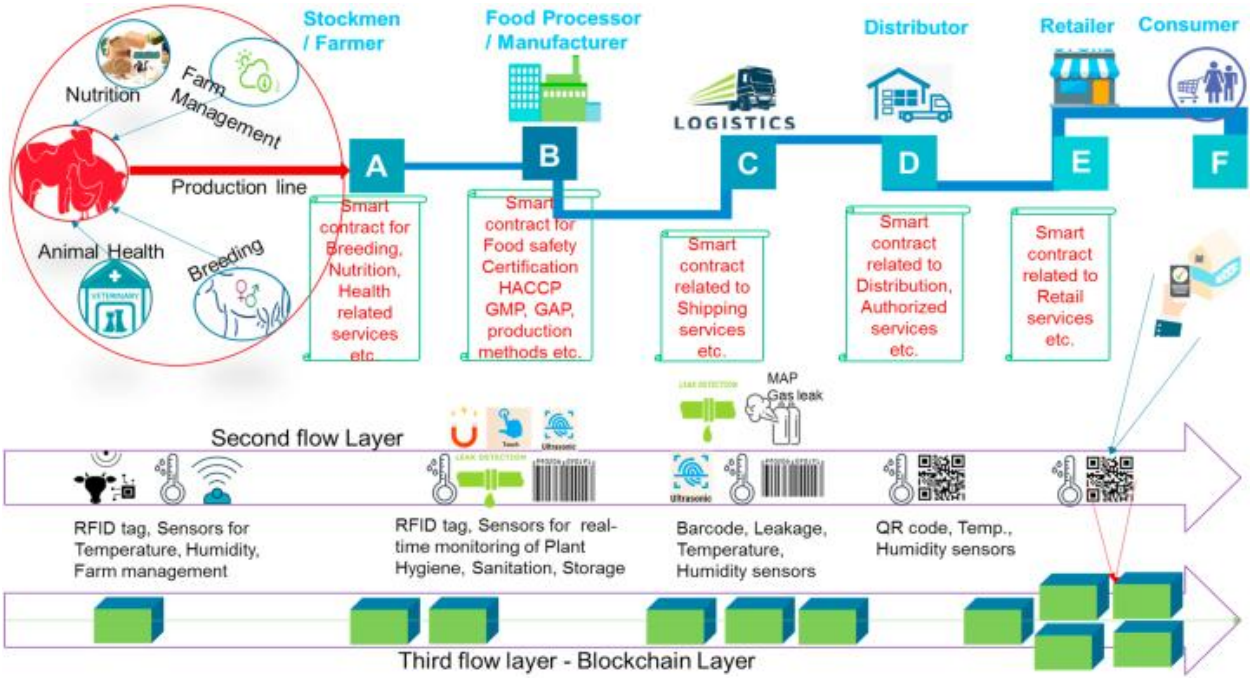


Figure 1. Blockchain technology driven food traceability. (Kamilaris et al., 2019)

The significance of real-time monitoring systems is increasing in the logistics of food supply chains (Kayikci et al., 2022:836). Therefore, using blockchain in the food industry is crucial for establishing a decentralised, unchangeable, transparent, dependable, and automated system for instantaneous monitoring and decision-making. IoT tools like RFID are commonly used in digital food traceability systems, with blockchain-based systems also seen as a promising solution (Kayikci et al., 2022:836).

While food supply chains have created and utilised traceability systems, none of them can fully meet the requirements of all food supply chains. This is because it is challenging to establish a universal traceability framework that allows for flexibility, scalability, and adaptability of the solutions for different food product value chains (Li et al., 2020:843). Hence, establishing a reliable and productive traceability system is crucial in the food industry. Research into blockchain-based traceability systems in the food industry is growing to support this endeavour (Ping et al., 2018:35).

The usage of blockchain technology for traceability is still in the early stages, and there is currently not widely accepted and cost-effective commercial application available (Ping et al., 2018:35) indicating the need for more extensive knowledge. Limited knowledge exists on the data structure needs and design of supply

chains essential for successful blockchain implementation in food supply chains (Dolgui et al., 2020:2184). Further, the effects of implementing blockchain traceability systems in food supply chains are not fully comprehended. Hence, it is crucial to combine existing research findings and introduce new ideas to promote the advancement and implementation of efficient blockchain-based traceability systems in the food industry (Dolgui et al., 2020:2184).

5.4. Blockchain technology: a solution to food traceability challenges

Blockchain can be utilized in the agri-food industry to develop a transparent and trustworthy food traceability system that monitors food products' journey from farm to table (Chun-Ting et al. 2020). This system would ensure that all production and supply chain stages are documented and verified, lowering the possibility of fraud, mistakes, and contamination (Antonucci et al. 2019). Accordingly, blockchain technology can boost food security, enhance transparency and traceability, and regain consumer trust in the safety and quality of food (Zhao et al. 2019). The use of blockchain technology has become a viable way to achieve seamless food traceability as concerns about supply chain transparency and food safety continue to grow (Kamath, 2018). Additionally, regulatory compliance is another driving force, as governments impose strict requirements for tracking food products to ensure public safety (Tasnim, 2020:73). Blockchain technology presents a promising solution to the above challenges, offering a decentralised, transparent, and secure way to track food products throughout their lifecycle.

Blockchain technology offers a robust solution to the challenges of food traceability. One of the key advantages of blockchain in food traceability is its ability to provide real-time data on food products. Traditional traceability systems often rely on manual record-keeping, which can lead to errors and delays in tracking products. In contrast, blockchain allows for the automatic recording of every transaction in a decentralized ledger, making it easier to trace food items at any point in the supply chain. Further, Wang et al., (2020:111) posits that blockchain-enabled food traceability allows for improved cybersecurity and reduced food fraud, by using strong cryptography and by identifying counterfeiting, dilatation, and adulteration, in support of better food security and safety.

One of the key advantages of blockchain is its decentralised nature. Unlike traditional systems that rely on a central authority, blockchain allows all stakeholders to access the same information in real-time. This transparency can significantly enhance trust among consumers and businesses alike. By providing a tamper-proof record of a product's journey, blockchain fosters confidence in the safety and quality of food products (Thume et al., 2022:219). Moreover, blockchain enhances the security of food traceability data. The decentralized nature of blockchain means that no single entity has control over the entire system, reducing the risk of data tampering. Each transaction is encrypted and linked to previous records, creating a secure chain of information that is resistant to fraud. This feature is particularly important in an industry where food fraud can have serious consequences for public health and safety (Tian et al., 2024:4812). By ensuring the authenticity of food products, blockchain technology helps build consumer confidence in the food supply.

Blockchain also enables real-time tracking of food products. With IoT (Internet of Things) devices integrated into the supply chain, data about temperature, humidity, and location can be recorded on the blockchain in real time. This capability allows for immediate responses to any deviations from safety standards, ensuring that food products are handled appropriately throughout their journey (Kumar et al., 2022).

Blockchain also facilitates greater collaboration among supply chain stakeholders. By providing a shared platform for recording and accessing data, all parties involved—farmers, processors, distributors, and retailers can work together more effectively. This collaboration not only improves communication but also allows for better alignment of practices and standards across the supply chain. As noted by Datta et al. (2023) enhanced collaboration through blockchain can lead to more efficient operations, reduced waste, and improved overall supply chain resilience.

Smart contracts, which are self-executing contracts with the terms of the agreement directly written into code, can further enhance blockchain's effectiveness in food traceability. These contracts can automate various processes, such as payments and compliance checks, reducing the need for intermediaries and minimising delays (Wang et al., 2022). This automation streamlines the supply chain, making it more efficient and less prone to human error.

The adoption of blockchain in food traceability presents significant opportunities for innovation and market differentiation. Companies that leverage blockchain technology can offer consumers verified information about the origin, quality, and safety of their food products. This transparency not only enhances brand reputation but also caters to the growing consumer preference for sustainably sourced and ethically produced food (Zhang et al., 2023:102). By embracing blockchain, businesses can set themselves apart in a competitive market and capitalize on the increasing demand for transparency and accountability in the food industry.

5.5. Challenges posed by blockchain technology in food traceability

While blockchain technology used in food traceability presents many opportunities, it also presents numerous challenges that may hinder traceability of food and their supply chains. These challenges need to be addressed to enable the successful use of blockchain technology to promote and enhance the capacity of food traceability.

5.5.1. Resistance to adoption

Resistance to the use of blockchain technology by the stakeholders is the first challenge. According to Singh et al. (2023:212) stakeholders within the food supply chain may exhibit reluctance to adopt blockchain technology due to a lack of understanding, fear of technological complexity, or concerns about disrupting established processes. Resistance to adopting blockchain technology is prevalent among stakeholders in the food supply chain. This resistance often stems from a lack of understanding of blockchain's benefits and functionalities. Ellahi et al. (2024:8944.) posits that many organizations are accustomed to traditional methods of record-keeping and may be hesitant to change established processes. Furthermore, the need for collaboration among various stakeholders can complicate the adoption process, as differing interests and levels of technological readiness can create friction (Ellahi et al., 2024:89).

5.5.2. Data security and privacy concerns

Data security and privacy concerns is another second challenge that if not addressed would hinder the successful use of blockchain technology in food traceability. While blockchain is lauded for its security features, concerns about data security privacy and the potential for unauthorized access persist. Ensuring that sensitive information is protected while maintaining transparency poses a complex challenge. Khan et al. (2023:680)

argues that there is a need for regulatory support and strategic investment in blockchain solutions to promote sustainability and competitiveness in the agri-food sector, highlighting the importance of addressing data security and privacy issues. Data privacy is another crucial factor that must be considered. While blockchain offers transparency, it also raises questions about who has access to the data and how it is used. Sensitive information regarding food sources, production methods, and supply chain logistics could be exposed if not managed properly. Ensuring that personal and proprietary data remains confidential while still allowing for transparency in the supply chain is a balancing act that requires careful consideration (Zhang et al., 2022).

5.5.3. Scalability

Scalability remains a significant challenge for blockchain in food traceability. As the volume of transactions increases, the blockchain must handle a larger amount of data without compromising speed or efficiency. Traditional blockchain systems can become slower as more nodes are added, which can hinder real-time tracking capabilities. Wang et al. (2022:6192) emphasizes that achieving the necessary scalability while maintaining the integrity and security of transactions is a critical concern for the industry.

Regardless of its potential for revolutionising product supply chains, blockchain technology faces obstacles preventing widespread adoption. Rejeb et al. (2020:27) addressed the obstacles in implementing blockchain technology in the food supply chain, focusing on technical, organisational, and regulatory issues. The global food supply chain includes participants from various regions around the world. Hence, it is a challenge to improve transparency, auditability, and reliability in various stages of food sector management, especially in the presence of constraints on data governance (Caro et al., 2018:2). Challenges commonly associated with utilising blockchain technology include restrictions on data storage capacity, scalability concerns, potential exposure of private sensitive data, and significant investment expenses (Zhao et al., 2019:83). Khan et al. (2023:668) argued that barriers such as high costs and lack of knowledge hinder the adoption of blockchain technology in food systems (Khan et al., 2023:668). The initial setup and operational costs associated with blockchain technology can be significant. Developing a blockchain infrastructure requires investment in technology, training, and ongoing maintenance.

6. Conclusion

Blockchain technology was found to address challenges encompassing food traceability. It offers solutions to longstanding issues related to transparency, safety, and efficiency in the food supply chain. Blockchain technology facilitates real-time tracking of food products from their origin to the consumer's table. This capability not only strengthens accountability among stakeholders but also empowers consumers with reliable information regarding the sourcing and handling of their food. It fosters trust and confidence in food safety, which is essential in a market, increasingly focused on quality and ethical sourcing. However, the adoption of blockchain in food traceability systems requires a collaborative effort among various participants in the food supply chain, including producers, processors, and retailers. There is a need for future research to focus on developing standards and protocols that facilitate seamless integration, ensuring that various stakeholders can efficiently share information. Empirical studies that evaluate the real-world effectiveness of blockchain technology implementations in diverse food supply chains, and food safety incidents, consumer behavior, and operational efficiency are needed. This would provide valuable insights for stakeholders in both food

traceability and food supply chains. There is also a need for studies to analyze the regulatory environments that affect blockchain adoption in food traceability so that new insights that promote the best practices and standardization efforts are made available to enable successful implementation.

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