Pioneering food safety: Blockchain’s integration in supply chain surveillance

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ABSTRACT

Ensuring food safety in a world facing escalating demand and complex supply chains is a pressing challenge. Despite increasing awareness, obstacles such as information distribution, financial limitations, and insufficient infrastructure impede food safety efforts. Blockchain technology presents a promising solution by improving transparency and traceability in supply chains, which are essential for tackling food safety issues. This study explores the integration of blockchain into food safety frameworks, emphasising its compatibility and potential to transform food production and distribution. Drawing on literature, it identifies key challenges to blockchain adoption, including regulatory frameworks and interoperability issues, and proposes strategies such as government intervention and standardisation to overcome them. Ultimately, blockchain holds immense promise in revolutionizing food safety practices, ensuring safe and nutritious food for all.

1. Introduction

Billions of individuals worldwide face the potential hazard of consuming unsafe food. Enhancing the efficiency and efficacy of food supply chains is an imperative task. Projections indicate that the global population will surpass 9 billion by 2050, necessitating a considerable increase of up to 70% in food production compared to current levels. Consequently, there is a pressing need for food production and distribution systems to transition towards heightened sustainability. Presently, the issue of food safety has garnered global attention, mainly due to various food safety scandals [1].

Today, the agriculture industry is under pressure due to the increasing world population and demand for sufficient, safe, and high-quality food products. At the same time, the current food supply chain has become more globalised [55], and the dependency on imported food has increased globally by approximately 50% between the years 2006 and 2020 [56]. Accessing adequate quantities of safe and nourishing food is vital in sustaining life and enhancing overall well-being. The consumption of unsafe food, which may harbour detrimental microorganisms, viruses, parasites, or chemical agents, is known to give rise to over 200 illnesses, spanning from gastrointestinal issues to various forms of cancer [2]. Nevertheless, many obstacles hinder the implementation of measures to ensure food safety. These challenges encompass deficiencies in disseminating pertinent information, the financial implications associated with the adoption of numerous food safety initiatives, the limited level of education among food handlers, inadequate food testing facilities, and constraints related to funding, equipment, and skilled workforce. In addition, the costs associated with training and education, and the absence of effective coordination among entities tasked with addressing food safety concerns further compound these challenges [3].

Effective management of food supplies is essential to guarantee the availability of safe and reasonably priced food for a growing global population. The global food chain can be described as a complex web of interconnected links, ranging from farming and processing to distribution and purchase. This complexity makes it challenging to address issues related to food safety and traceability, which are crucial for enhancing public health and building consumers’ trust. Traditional methods of tracking and auditing the food chain have failed to address these issues adequately, being more descriptive than prescriptive and highly vulnerable to fraud and inefficiencies.

Blockchain technology offers an innovative solution that could revolutionise food safety and supply chain monitoring. The use of blockchain has emerged as a groundbreaking tool in food supply...
management, providing a decentralised and transparent framework that offers several significant advantages aimed at resolving long-standing issues in the food sector. Blockchain is a novel technology that can significantly impact various industries, including supply chain, healthcare, finance, energy and real estate [4].

In the context of food supply chains, blockchain can enhance transparency, accountability, and efficiency. This article explores the integration of blockchain technology with existing food safety frameworks, arguing that the two are compatible and interdependent in achieving their shared objectives. This review discusses how blockchain technology can be adopted for food supply chain surveillance, the benefits of its implementation, and the improvements it will bring to food safety. In this way, due to a blockchain technology implementation, we are not only preserving the people’s health but also helping the food industry become more reliable and environmentally friendly for the next generations.

Blockchain is not just a new technological tool in the field of food safety; it is a revolution in the global food supply chain. By thoroughly examining blockchain’s potential in overseeing supply chains, this study aims to illustrate the significant impact this technology can have on enhancing food safety standards worldwide. Through this exploration, the article endeavours to illuminate the transformative influence of blockchain technology on instigating changes in food production, supply chain monitoring, and the broader landscape of consumers and the food industry.

2. Background

[S] suggested that primary concerns regarding food safety pertain to bacterial pathogens, pesticide residues, and mycotoxins, compounded by deficiencies in food safety knowledge and suitable governmental legislation and enforcement. Although many informal food vendors offer economical options for food procurement, the safety of products retail in such establishments is compromised by unsanitary food handling practices and the absence of proper sanitation facilities, running water, refrigeration, and disinfection [6]. Regrettably, the public’s indifferent stance towards food safety protocols, disjointed strategies for food regulation, and inadequate enforcement of laws and regulatory thresholds have worsened the issues surrounding food safety protocols and foodborne hazards. This situation is highlighted by [7]. Moreover, inefficiencies in the food supply chain, deficient traceability, and a lack of comprehension regarding food safety and quality standards have all played a role in exacerbating these challenges. Furthermore, additional significant hurdles to food safety encompass a lack of proactive risk management attitudes and a reluctance to draw lessons from mishaps, close calls, and safety indicators [8].

Conventional methods used to trace the origins of contaminated items are often slow and ineffective, resulting in delayed response efforts and putting more individuals at risk. The capability to promptly trace back contaminated goods can substantially alleviate the repercussions of such occurrences [9]. [10] recommended that the principal obstacles to food safety in developing nations are the ramifications of failing to adhere to international food safety protocols, which should be perceived as catalysts for enhancing food safety standards. The structures for food regulation are deficient due to limited resources and the involvement of numerous agencies, rendering the management of control measures challenging. In the local market, food safety is hampered by inadequate infrastructure and facilities, resulting in the proliferation of contaminated food items. These foundational obstacles have impeded efforts to instil food safety practices among individuals, while the nonchalant attitudes of consumers and regulators have gained worrisome traction.

Numerous technologies, such as Radio Frequency Identification (RFID), sensor networks, and data mining, have been incorporated into conventional food supply chain systems to eliminate unsafe food products from the chain. However, these technologies are deemed insufficient for the contemporary supply chain market. According to [11], the emerging technology of blockchain has the potential to address safety and tracking challenges by leveraging features such as transparency, decentralisation, distribution, and immutability.

Blockchain-based transparency arises from the highly secure nature of the technology since it records all transactions irrefutably. This ensures that every stakeholder involved in a network can view the same data in real-time, which may help to minimise fraud and mistakes [67]. Indeed, while the use of blockchain provides transparency and increases the ability to track transactions, it also poses a disadvantage due to privacy issues. Another potential problem is that the blockchain is open to the public. For instance, the exchanging parties might not be willing to disclose specific transaction details, which could be useful to the competing firms [69].

The decentralisation mentioned here means that the flow of control and power does not come from a specific centre. This may minimise the threats relating to a single point of failure and diminish the dangers arising from centralised systems [68]. Decentralisation removes the possibility of a single controlling entity, which can cause power loss and censorship. However, it also poses certain risks, such as requiring consensus from multiple parties, which may be time-consuming in decision-making moments. Furthermore, there are concerns because no authority oversees the data or the network, leading to problems concerning regulations and laws [70].

A distributed system makes blockchain more secure and resistant to hazardous attacks since there is no single point of contention. However, this distribution creates greater difficulty in integrating blockchain with other systems into their framework. It may also cause the problem of replication, where the same data is located on different network nodes, leading to increased storage capacities requirements and network inefficiency [12].

Understanding properties of blockchains is crucial because data added to the chain cannot be changed, a feature known as immutability. This enhances auditability and trust. However, it also means that errors cannot be easily corrected, and there is no way to update or delete data in response to changing circumstances or legal requirements. This can be particularly problematic when incorrect or fraudulent information is recorded on the blockchain [34].

Blockchain technology is an immutable digital data management system designed for storing and retrieving interconnected data within a network. These data are structured into blocks, each containing a set of transactions or information, which are linked together in chronological order to form a secure and transparent chain. The immutable nature of blockchain has garnered significant traction across various sectors. There exist four primary domains wherein blockchain can enhance the food supply chain’s efficiency, ensuring data precision, enhancing supply chain efficiency, facilitating intelligent agriculture, and monitoring food safety [12].

Being a decentralised form of database, the ledger put in place by blockchain is definitive and fully transparent. This means that once data is recorded, it cannot be changed without consensus, reducing the possibilities of data manipulation or errors. This precision is crucial for ensuring the authenticity and quality of the food supply chain from the farm to the consumer’s table [64]. Blockchain can streamline operations, as demonstrated by smart contracts, which replace manual interventions with automated procedures. This result in increased efficiency in handling products through transactions, decreased costs, and the convenience of tracking products in cases of complaints, product recalls, or foodborne illnesses [65].

Blockchain can also support intelligent agriculture through real-time data sharing among various members. This data includes information about crop conditions, climate, and market trends, aiding farmers in decision-making processes and enabling the proper use of resources to enhance crop production [66]. In this way, blockchain technology can trace food products through the supply chain in real-time, allowing food safety issues to be detected easily. It also helps verify the credibility of
products labelled as organic or fair trade, thereby enhancing consumer confidence. These domains are interrelated and contribute to a stronger and more dynamic food system, making the availability and accessibility of food safer and more sustainable.

Blockchain technology has been identified as one of these innovative supply chain [13]. The implementation of food traceability has been technologies, with blockchain-based initiatives playing a key role in new information technologies associated with Industry 4.0 is leading to minimising food loss and waste. The advancement of digitalisation and decentralisation technology, blockchain consists of time-stamped blocks linked by a cryptographic hash. It has been widely accepted as a solution to the underlying trust and security issues in information transparency and the prevention of tampering [49, 50].

Controlling the packaging and tracking of food is challenging in today’s world, hence the adoption of blockchain technology to increase food security. Blockchain is a decentralised, immutable, and highly secure ledger system for maintaining the record of each transaction in the food chain. This transparency is essential, especially in the provision of food, as it allows stakeholders to familiarise themselves with the flow of food from farm to the consumer’s table [61]. However, the conventional systems present additional barriers to implementing adequate documentation, record-keeping, and tracking processes that enable companies to identify the source of their foods and respond effectively to contamination.

Blockchain ensures data is distributed with no central control, avoiding the fraud and errors common in traditional centralised systems. Decentralisation is challenging because food supply chains are usually centralised, with food accumulated in small quantities, making distribution difficult and vulnerable for corruption [62]. Blockchain’s decentralisation means data is stored in blocks across various nodes, offering better protection again hacking or data loss. Deployment is difficult in conventional architectures due to large centres housing databases that are more prone to hacking and collapse [63]. One disadvantage of blockchain is that once data is stored, it cannot be changed, which is essential for certifying the authenticity of records related to food safety. Immutability can be problematic because, in traditional database systems, records can be altered and compromised, leaving consumers and other stakeholders in doubt.

3. Enhancing food safety with blockchain

3.1. Transparency and traceability in the supply chain

Ensuring transparency and traceability in the food supply chain is emerging as a crucial factor in addressing food safety challenges and minimising food loss and waste. The advancement of digitalisation and new information technologies associated with Industry 4.0 is leading to notable enhancements in traceability systems within the supply chain. Blockchain technology has been identified as one of these innovative technologies, with blockchain-based initiatives playing a key role in enhancing transparency and efficiency in the agricultural and food supply chain [13]. The implementation of food traceability has been positively acknowledged for its ability to mitigate concerns related to food safety incidents. Effective food traceability not only aids government agencies and food producers in promptly identifying the source of food contamination during outbreaks or contamination events but also helps in addressing challenges arising from the involvement of multiple stakeholders in the food production system and the lack of technical infrastructure for synchronized food safety monitoring across the system. Recent studies have highlighted the promising potential of emerging digital solutions like blockchain technology in mitigating the deficiencies of traditional food traceability systems [12].

Over the past few decades, there has been a noticeable escalation in issues related to food safety and traceability. To mitigate risks of accidents and malpractices, the establishment of a Food Safety Traceability System (FSTS) has become imperative for tracking food from its origin to the end consumer. These traceability systems play a crucial role in monitoring the movement of food along the supply chain, starting from farms to retail outlets [11]. Addressing consumer apprehensions regarding food quality and safety has become paramount as the food industry increasingly prioritises customer satisfaction. Therefore, the implementation of an FSTS is essential to ensure the delivery of high-quality food products to consumers. By tracking all stages of food production, from raw material sourcing to consumption and disposal, FSTS facilitates comprehensive food product traceability across the supply chain [14]. FSTS delivers substantial value to consumers by focusing on product recalls, eliminating non-consumable items, and investigating the underlying causes of food safety incidents [15]. These safety measures serve to prevent the inception of fraud and uphold the quality of food products. Numerous countries have introduced various standards, laws, guidelines, and regulations to strengthen food safety protocols [16].

In the realm of food traceability, novel technologies are emerging, such as radio frequency identification (RFID) and wireless sensor networks (WSN), and among others [17] elucidates the approach to traceability grounded in RFID and blockchain technology. The study concentrates on two categories of food: fresh fruits and vegetables and meats, including pork, mutton, chicken, and beef. RFID technology is predominantly employed in production, processing, warehousing, distribution, and sales, while blockchain technology serves as a mechanism to ensure the veracity and credibility of the information disseminated within this traceability framework. Blockchain technology renders the information transparent and accessible, thereby enabling logistics enterprises to conduct real-time monitoring of agri-food products [17]. [18] integrated RFID, wireless sensor networks (WSN), and data mining in an e-pedigree food traceability system. WSN is a technology founded on sensor nodes used for detection, processing, and communication. These sensor nodes gather environmental data, such as temperature and humidity, which are subsequently converted into digital form and archived in a database. Presently, smartphones are ubiquitous worldwide, and this technology can serve as gateways to aggregate sensor data and transmit it to the server [18].

[51] developed a framework for a supply chain traceability system utilising blockchain and radio frequency identification (RFID) technology. The framework comprises a decentralised blockchain-based data storage platform for managing data and an RFID system at the packaging level for collecting and storing data. The study incorporated a consortium blockchain into the application, selecting Fabric 2.0 in Hyperledger as the development platform. The deployable blockchain-based platform designed in this study can contribute for distributed data management, and the algorithm used ensures data security. The system includes a novel blockchain data structure embedded in the RFID tag. Upon scanning the tag, the details are written in a block connected to previous blocks; simultaneously, the details are recorded on the blockchain platforms. The system operates without a battery, activating when an RFID reader is nearby. It was noted that the new traceability system allows for easier product tracking and can be further improved for industrial setting [51].

[52] proposed a decentralised traceability system to address the food safety issues by combining blockchain and an electronic product code information services network [52]. [53] proposed a blockchain–IoT based food traceability system that incorporates blockchain, IoT, and fuzzy logic for the efficient handling of perishable food. To meet the demands of food traceability, shipment transit time, stakeholders’ rating, and shipment volume, a new consensus solution was designed based on a simplified multidimensional model that includes shipment transit time, transporter’s score, and shipment loads [53]. [54] investigated a current beef supply chain project using blockchain and IoT for event tracking and beef origin authentication, presenting two directions to enhance data credibility and shareholder confidence in the blockchain and IoT-supported food supply chain [54].
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pointed that current blockchain-based traceability systems are mostly applied to fruit and vegetables, meat, dairy products. A blockchain-based traceability system can help design and implement a secure and tamper-proof system without data centralisation, making the process fully auditable for tracking and decision-making with process automation and real-time data monitoring. The study discusses India’s public food distribution programme (PDS), building a perception-based model of social causations of food insecurity with suggested remedies. This demonstrates the novelty of using blockchain in the design of food traceability systems. The study employed Soft System Methodology (SSM) to identify necessary changes within PDS through learning and inquiry. It uses system thinking and action research to build a reasonable and defensible model for presenting solutions. This research highlighted that the adoption of a blockchain-based food traceability system enhanced food value chains, meeting the needs of the beneficiaries [57].

3.2. Accountability and real-time surveillance

A study conducted by [19] unveiled that diverse blockchains implement distinct forms and mechanisms of accountability in innovative ways previously underemphasised in scholarly works. Notably, the research indicates that accountability does not necessarily hinge on a principal-agent relationship and can still be evident in less pure implementations of blockchain technology involving a broad spectrum of stakeholders. This contrasts with earlier assertions in interdisciplinary literature regarding blockchain utilisation. The study also highlights that similar accountability subcategories function quite differently across public, private, and consortium blockchains, and a negative correlation exists between trust and consensus establishment as blockchains transition from public to private formats [19]. [20] proposed that implementing a permissioned blockchain influences accountability through three interconnected mechanisms: the ledger, the code, and the individuals involved. While blockchains are commonly praised for their capacity to enhance transparency by making transactions visible, the authors argue that this perspective is inadequate. Merely promoting transparency does not suffice to fulfill the obligation of accountability, as it could lead to selective information disclosure or concealment.

The growing emphasis on food safety has become significantly important, leading to an increased demand for real-time surveillance to promptly detect and address safety issues in the food sector. In their pioneering work [21], developed an innovative colorimetric sensor array specifically designed for real-time monitoring of beef freshness. The sensor tag videos were captured within a colour controller lightbox using a smartphone to generate image datasets. These images were subsequently partitioned randomly into training and testing sets and then inputted into convolutional neural networks (CNNs) to train the food freshness classification model. The findings demonstrated that all four CNN architectures accurately distinguished freshness with an accuracy exceeding 96%, thereby enhancing the precision of biosensor identification. In a separate study [22], employed UiO-66-Br (selected for its superior binding energy) on an ice-templated chitosan substrate (ice-templated dye @UiO) to establish sensor arrays. They introduced a sensitive, non-destructive product platform, enabling consumers to conveniently monitor shrimp freshness in real time using the Wide-Slice Residual Network 50, achieving an impressive accuracy of up to 99.94%. Four state-of-the-art DCNN models underwent training with 31,584 annotated images, while 13,537 images were reserved for testing purposes. Moreover, integrating deep learning systems into computer vision can enhance food production monitoring.

3.3. Use of blockchain for food traceability through value chain

The food value chain, encompassing the array of intermediaries involved in transporting raw produce such as freshly harvested agricultural crops, products, and processed foods, constitutes a system of sequence of activities connecting food producers with consumers across organisational interfaces [43]. The food supply value system can therefore encompass producers or growers, processors, wholesalers or distributors, retailers, importers or exporters. These entities engage in activities such as handling, packaging, transporting, storing, and trading these products, which constitute goods for contracts, services, and financial transactions [43]. These processes, alone with the essential stakeholders involved, form a highly complex, disorderly, and evolving system of processes whose behaviour affects the system’s performance [44, 45]. A supply value chain depends on the timely and proper flow of information, ensuring the effectiveness and efficiency of processes. Numerous studies into information-rich supply value propositions have led to improvements in mathematical modelling, information handling, supply chain strategies, and data mining, facilitated by technological reliance, virtualisation, Internet of things (IoT), radio frequency identifiers (RFIDs), and recent blockchain technologies [46, 47].

[48] highlighted the advantages of blockchain technology such as shared governance and business, fault tolerance, tamper-proof, traceability and authorisation. In value chain design, operators seek to be part of a system while not blindly trusting other operators. Through blockchain technology, they can integrate their governance and operational responsibilities. The Paxos consensus protocol, defining an agreement among corresponding operators on operations within the system, plays a crucial role. Furthermore, the data is localised and mirrored within each node, ensuring robust coping with data loss. When a transaction occurs, a new block is appended to the blockchain with information details, including the timestamp. This new block is approved by the consensus protocol endorsed by the value chain operators, making the blockchain auditable [48].

To evaluate the success of utilising blockchain technology in supply chain surveillance, various types of data must be collected and retained. This entails information detailing the farms that produced food items, the production processes employed, and the agricultural practices adhered to during crop cultivation and harvesting to meet traceability standards [58]. Food data capture encompasses information regarding the handling of food products, including temperature and packaging, as well as processing to ensure food quality and safety throughout the manufacturing and distribution channels [59]. Comprehensive documentation of transportation and storage condition, such as temperature, humidity, and duration of exposure to these conditions, is essential for determining factors contributing to spoilage and contamination of food products. Records of inspections, quality test procedures, and certification details compliant with standards like HACCP and ISO 22000 should also be maintained. The end consumer ultimately determines the quality of food products sold through distribution channels, underscoring the importance of gathering information on the distribution network, sales points, and consumers feedback [60]. By implementing these metrics in a blockchain, stakeholders can enhance food safety and significantly reduce opportunities for fraud in the food industry. The inherent structure of the blockchain ensures that once information is entered, it cannot be altered, providing a trust-free and transparent record of the journey of food products from farm to consumer’s table.

4. Challenges to blockchain integration in food safety

4.1. Adoption barriers

Research conducted by [4] has identified ten notable obstacles to the adoption of blockchain technology using a comprehensive review of literature and insights from experts. These obstacles were further classified into two groups, namely influential and influenced, using the DEMATEL technique. The outcomes of this research revealed that the barriers to the ‘influential group’ category demand heightened attention from supply chain partners to address them effectively. The key barriers in the influential category include ‘Deficiency in information sharing’, ‘Challenges in trust management’, and ‘Absence of updated technologies’, necessitating immediate action from stakeholders in the supply
chain seeking to incorporate blockchain technology. These discoveries play a pivotal role in enhancing the decision-making processes of managers and the digital strategies related to blockchain within enterprises, shedding light on the optimal approaches to implementing this technology [23], asserted that the obstacles to integrating blockchain technologies exert a gradual and tangible influence on organisational operational efficiency. This phenomenon necessitates further explanation through the establishment of universally recognised procedures within the industry. Ultimately, scholars perceive blockchain technology not as a panacea for all organisational challenges, but as a foundational component that enhances operational efficiency.

[24] discovered that obstacles related to 'organisational', 'strategic', and 'social' factors had impeded the implementation of Industry 4.0 in the food supply chain, with a negative impact exceeding 50%. The primary barriers include senior management's inadequate perception of digitisation and reluctance to embrace a sustainable food supply chain enabled by Industry 4.0. The key solution lies in the commitment and support of top management, alongside government initiatives offering financial incentives and tax relief. Meanwhile, [25] highlighted persistent challenges in the adoption of blockchain technology within industrial contexts, attributing the hindrances to a lack of knowledge and awareness.

4.2. Regulatory frameworks

Blockchain technology is a form of digital ledger technology that requires numerous computers and hardware for data mining and storage, resulting in heightened initial implementation costs and validation expenses. However, this obstacle can be overcome through the utilisation of sophisticated concepts within a digital framework, as expounded by [26]. Globally, blockchain technology is commonly associated with its application in cryptocurrencies. The substantial volatility and frequent fluctuations in the value and market share of cryptocurrencies have a detrimental impact on the reputation of blockchain technology [27]. A notable deficiency persists in the uniformity of knowledge and comprehension among technical specialists and policymakers. The lawful execution of smart contracts within a distributed ledger technology (DLT) framework, particularly concerning issues such as enforceability, jurisdiction, and the application of contractual legal principles, remains a critical and contentious matter [28]. The preservation of confidentiality in information remains a limiting factor as industries exhibit reluctance to share proprietary data with market competitors [42]. The absence of standardised protocols may impede the integration of blockchain technology within the practical realm of the food industry. Consequently, the synchronisation and standardisation of diverse blockchain platforms in the food sector pose additional challenges [29].

Regulations about blockchain are trailing behind, and the supervision of compliance activities remains incomplete. Serving as a mechanism for social resource allocation, laws and regulations play a role in simplifying intricate social relationships, reducing transaction expenses, and supporting the stable functioning of society. However, as a nascent Internet technology, blockchain technology inevitably clashes with existing legal frameworks, presenting significant challenges to current laws and regulations, notably in the realms of safeguarding data within blockchain systems and determining pricing structures and liability allocation following the onset of risks [30].

4.3. Interoperability issues

Interoperability refers to the capability of diverse information technology systems or software applications to communicate seamlessly to exchange, interpret, and utilise data [31]. Genuine interoperability in systems necessitates the ability to exchange data utilising a uniform data format (syntactic interoperability) and the capacity to comprehend shared data with mutual meaning (semantic interoperability) [32]. The significance and requirement of facilitating interoperability for enhancing the safety and defence of the global food system were emphasised by [31]. They highlighted the inadequacy of various technology solution providers in achieving interoperability. The necessity of promoting interoperability among various datasets to enhance outbreak epidemiology, investigation, and response was underscored by the EFSA Panel on Biological Hazards. Despite proposals of frameworks and ontologies as means to enable interoperability, there has been a deficiency in implementation and widespread adoption. Interoperability is a persistent challenge in the food sector and various other industries, including electronic healthcare records, health informatics, nutrition sciences and diets, manufacturing, and engineering [32].

The requirement for standards and protocols is heightened by the demand for interoperability throughout the food supply chain, as indicated by [25]. The adoption of blockchain-based solutions faces obstacles due to the absence of a consensus protocol. The food industry has faced vulnerabilities due to the lack of transparency in the supply chain. Beyond regulating blockchain utilisation, standardising the terminology is crucial. Standardisation plays a vital role in maximising the benefits of technologies like blockchain, which offer numerous advantages, and achieving consensus on standards ensures improved governance across food supply chains [25].

5. Strategies for overcoming challenges

5.1. Facilitating adoption

Governmental assistance has the potential to exert a substantial influence on the integration of blockchain technology. Governments may extend financial incentives and pilot schemes to foster technological advancements. The pivotal role of the government in the acceptance and dissemination of innovations is manifested through information dissemination, formulation of research and development strategies, provision of incentives, establishment and improvement of infrastructure, execution of pilot initiatives, provision of tax exemptions, as well as delivery of consultancy and guidance services [33]. Various external prerequisites have been identified as dual-edged elements that impact the decisions of food enterprises to implement blockchain technology. Individual farmers’ adoption of new technologies and methodologies is perceived as more perilous in the absence of government intervention.

5.2. Shaping regulatory environments

Regulatory bodies should determine and provide for the proper standards and procedures for blockchain implementation processes in the food industry. The regulations, however, should be based on data quality, interoperability, and data security guarantees to allow the technology to interchange the supply chain for the various sourcing points seamlessly. Innovation together with the interest of the public, is the aspect that government should stimulate through the development of private-public partnerships. The partnerships between such sectors translate the abilities of both sides to the advantages, where private enterprises apply their competencies, and through regulations, the government ensures compliance [34].

Before mainstream use, regulatory authorities should encourage the test-bedding of blockchain’s low, often-sliced applications in a real-world scenario. On the other hand, those pilots can also show regulators the technical points when connecting with blockchain and thus help form the laws they need in the future. The evolution of blockchain and the creation of its framework must be engaged by all interested parties, which are producers, retailers, consumers and technologists. Collaboration can result in forming shared goals and gaining staff understanding of the technology and its limitations. The regulatory panel should provide education and training to the industry’s participants to help them embrace their roles effectively in the use of blockchain technology. The area is intended to include blockchain data management and its legal
and ethical implications [35].

Consumer protection is essential, and it is very important to consider the role of consumers in the regulatory process. They bring to the surface issues that the general consumers face, from food safety to data privacy concerns, when they give their opinion, thereby influencing the innovation policies that meet the challenges. Regulatory frameworks should be responsive equivalently along with technological solutions for their timely unfolding. Alongside the continuous innovation in blockchain technology, regulations should be adjusted accordingly to make sure that they are keeping up and that their systems are solid and up to date. Via international food supply chains, exacting global cooperation is important. These are some examples of how regulating international deals can lead to the widespread use of blockchain, which has strong and internationally accepted rules for food safety protection.

5.3. Promoting interoperability and standardisation

Blockchain technology holds the potential to effectively address various challenges, such as security, scalability, and interoperability, by facilitating efficient interactions among organisations that have adopted blockchain platforms. This enables them to securely manage data across various legacy systems securely, enhancing overall workflow efficiency [36]. The task of ensuring blockchain interoperability while upholding the fundamental features of blockchain poses a significant challenge. It is imperative to develop an approach that preserves the distinct characteristics of blockchains and adeptly manages state changes, such as data appending and validation procedures. Furthermore, cross-communication among integrated blockchain platforms should align with the specific blockchain platform being utilized, including sharing a similar consensus mechanism [37]. According to [38], the implementation of a standardized framework can greatly improve food traceability, enhance efficiencies within the food supply chain, promote data interoperability, strengthen data governance practices, and establish identification standards for products, assets, participating parties, locations, business processes, and chronological sequence.

Fig. 1 showcases a flowchart related to blockchain technology and its application in food safety. It outlines the benefits, such as transparency and traceability in the food supply chain, as well as challenges, like adoption barriers and regulatory frameworks. Additionally, it suggests strategies for overcoming these challenges, including facilitating adoption and promoting interoperability.

[39] conducted a study on ChainSCAN, a three-layer architecture for a fully decentralised SCM system based on blockchain technology. This system aims to safeguard data security and privacy, eliminating traditional SCMs' vulnerabilities. Moreover, ChainSCAN establishes a transparent setting to ensure the physical security of assets against theft and to record all activities within the food supply chain. By employing four smart contracts, ChainSCAN automates and governs the interactions among supply chain participants and the ledger, promoting the implementation of best practices across all organisations involved in the supply chain. Additionally, ChainSCAN features a notification mechanism that automatically informs consumers of food recalls and/or potential unethical behaviours.

6. Future research directions

[40] examines the inception, practical applications, and hurdles encountered in incorporating blockchain technology alongside other innovations such as the Internet of Things (IoT) within the food industry. Their apprehensions encompass issues related to traceability, security protocols, authentication procedures, production processes, automation mechanisms, logistical operations, storage practices, digital identification methods, and customer data management [41]. contend in their analysis that blockchain technology can be synergistically paired with IoT solutions to facilitate transparency within Food Supply Chains (FSCs) effectively.

Transparency is among the most potent forces in ensuring consumer trust when blockchain is introduced into the food supply chain. Blockchain creates a deep mine of information that makes it very difficult to tamper with data once it has been entered, thus making sure that claims about the authenticity of food products comply. In addition, this technology can be used to prevent food fraud. Next generation blockchain platforms should have the ability to be adaptive and interoperable, handling higher quantities of information while fitting in seamlessly...
with the infrastructure already in place. It will also cover knowing who is involved with food products at various points in the chain and whether they are true. There is a growing necessity for improvement in the technology behind the contracts and operations for the organisations that work within the supply chains, and this is soon to be a new stand-alone centre of the industry. The food safety apps shall focus on replacing the established operations and practices with new ones that guarantee healthy and secure food products.

Although blockchain has many valuable properties, problems arise from its complex structure, including the standardisation of the systems and interoperability. It is the job of concerned parties to join efforts to beat down these roadblocks so that the complete potential of blockchain in food safety is realized. Blockchain technology is a strong candidate for reforming food safety management by introducing new policy options, public openness, and improved transaction processes. As technology grows, more innovative solutions will probably appear to solve food safety tasks worldwide.

Table 1 provides an overview of various future directions in food safety technology, including integrating blockchain and IoT, transparency enhancements, contract technology improvements, efforts to address blockchain complexities, and innovations in food safety practices.

<table>
<thead>
<tr>
<th>Future Direction</th>
<th>Description</th>
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<tbody>
<tr>
<td>Blockchain &amp; IoT Integration</td>
<td>Enhancing the food industry with blockchain and IoT, tackling traceability, security, automation, and data management challenges.</td>
</tr>
<tr>
<td>Transparency Enhancement</td>
<td>Blockchain ensures trust by preventing data tampering and fraud in food supply chains, with next-gen platforms prioritizing adaptability and interoperability for seamless information management.</td>
</tr>
<tr>
<td>Contract Tech Improvement</td>
<td>Evolving contract and operational tech within food chains for heightened safety and security, potentially becoming a standalone industry focus.</td>
</tr>
<tr>
<td>Addressing Blockchain Complexity</td>
<td>Collaboration is needed to standardize and improve interoperability in blockchain, vital for realizing its full potential in food safety. It offers opportunities for reforming safety systems through policy, transparency, and streamlined transactions.</td>
</tr>
<tr>
<td>Innovation in Food Safety</td>
<td>Emerging technologies like blockchain offer new avenues for revolutionizing global food safety, introducing novel approaches and standards to ensure food security.</td>
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</tbody>
</table>

7. Conclusion

Blockchain technology presents an ultimate solution to ramp up food safety challenges by implementing an effective food traceability system. Its decentralised and transparent framework is unique and can be successfully used to produce transparent and traceable food. However, the participation of blockchain in this process is faced with several challenges, such as interoperability, regulatory barriers, and the adoption of blockchain technology in other sectors. In the face of these challenges, however, some strategies for eliminating these difficulties have originated. Support programs, financial grants, and pilot implementations can facilitate the widespread adoption of blockchain technology while having guideline authorities by regulating and creating standard and procedure frameworks. It is also important to develop guidelines that standardize communication between the blockchain platforms and the existing systems to make the data exchange and governance efficient.

To achieve the full potential of blockchain as a safety-related initiative, key participants along the supply chain, e.g., manufacturers, retailers, consumers and regulatory institutions, should collaborate and develop common goals. By collaborating through the process, we can effortlessly bridge divisions, implement effective methodologies, and leverage the power of blockchain to keep up with the rising concerns about the safety and quality of food. This cooperation should be a matter of high priority regarding transparency, security, and innovation to gain consumers’ trust and make our food systems more resistant. All stakeholders need to consider integrating blockchain into their system, as it offers a great deal for food safety. This is the time to stand up and say that it is up to us to shape a fresh, more transparent, and sustainable food chain which will serve the people of today and generations to come.

CRediT authorship contribution statement

Keru Duan: Writing – review & editing, Writing – original draft.
Helen Onyeaka: Writing – review & editing, Writing – original draft.
Gu Pang: Writing – review & editing, Writing – original draft. Zeyuan Meng: Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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