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Blockchain technology in the food supply chain: a way towards circular economy and sustainability

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The current status of the global food supply chain offers several challenges, particularly those related to traceability, transparency, and sustainability. Blockchain technology is recognized as a revolutionary tool that can revolutionize a wide range of sectors, and its implementation in food supply chains shows immense potential for improving circular economy practices and ensuring sustainability. The implementation of blockchain technology in the food supply chain and its tremendous influence on building a more sustainable and circular economy are examined in this review paper. Blockchain, with its decentralized and transparent characteristics, provides a unique approach for improving traceability and decreasing fraud in the food supply chain. This article investigates the many ways in which blockchain, including smart contracts, might increase efficiency and encourage sustainable behavior, eventually decreasing waste. Furthermore, the paper discusses the intriguing prospects of combining blockchain with cutting-edge technologies like the Internet of Things (IoT) and Artificial Intelligence (AI) to transform the food supply chain. Furthermore, using examples, we examine real-world applications, advantages, and constraints of blockchain adoption in the food business. The report finishes with insights into blockchain technology's possible future as an amplifier for increasing transparency, traceability, waste reduction, and improved sustainability in the worldwide food industry.

Sustainability spotlight

Our work highlights the importance of blockchain technology in improving global food supply chain by enhancing traceability, efficiency, and transparency, thereby reducing food waste. Blockchain enables real-time monitoring and optimizes resource use, in turn minimizing environmental impact. This advancement is a transition towards circular economy, a sustainable food system, and aligns with the United Nations' Sustainable Development Goals (SDGs), particularly Goal 12: Responsible Consumption and Production and Goal 9: Industry, Innovation, and Infrastructure.

1 Introduction

The global food business confronts new challenges such as traceability, transparency, and sustainability, encouraging the development of novel technologies. Conventional supply chains sometimes fail to satisfy expectations, resulting in concerns such as food fraud, waste, and a negative impact on the environment. Blockchain technology (BCT) has emerged as a game changer, providing a decentralized and secure system to improve trust, accessibility, and accountability during the food supply chain.[1] The confidentiality, accessibility, and integrity of all transactions and data are ensured by the cutting-edge, decentralized, and distributive technology known as blockchain. Peer-to-peer networks commonly utilize a shared, public, distributed ledger to securely store and manage data by employing cryptographic techniques for data protection.[2–4] Blockchain is a decentralized digital ledger that is shared over a network. It is very secure for commercial transactions since the data won't be altered without modifying earlier documents, which requires the consent of all or most of the involved parties. The technology has numerous applications across various industries, including the development of intelligent agreements to detect and prevent financial fraud, as well as the secure transfer of health records between healthcare providers. By building an unquestionable log in the shared ledger, blockchain offers a consensus mechanism approach that enables participants to be aware of every event and transaction. The banking, supply-chain management, logistics, housing, finance, medical, digital medical records, copyrights, entertainment, and sustainable energy sectors are just a few of the businesses that have been impacted. Its decentralized, verifiable, and unchangeable nature contributes to its continuing to expand its presence and influence in various industries. BCT has successfully transformed many supply chains, but there are still usability, safety, confidentiality, and financial issues.[5,6]

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In addition to altering the supply chain operations of many industries, it contributes to the functionality and safety of current digital stages like the Internet of Things (IoT) as well as other Industry 4.0 associated technology.[7] The standards for managing privacy and security vary by industry. Every stage of the supply chain, from the purchasing of raw materials to the delivery of commodities to customers, can be revolutionized by blockchain.[8,9] It also makes supply chain reengineering possible by developing a blockchain-based BPR (Business Process Reengineering) architecture.[2] Each transaction may be rebuilt to go more swiftly and safely using BCT. The blockchain industry is expected to increase at an average yearly growth rate of 79.6% from USD 241.9 million in 2016 to USD 7683.7 million by 2022.[10] Up to 10% of global GDP is anticipated to be held on the blockchains by 2025.[11] Blockchain is seen as an emerging technology with the potential to assist a wide range of businesses.[12]

Supply chain's security and transparency are ensured by the way the blockchain structure is set up. Below is an elucidation of the fundamental mechanism of a standard BCT. A scientific procedure, utilizing agreements, creates a 256 bit hash number for every block in the blockchain. A secure and independent blockchain is formed by linking the blocks based on the hash of the preceding block. Prior to inclusion on the blockchain, blocks must undergo validation, a process commonly referred to as "blockchain mining" or proof of work. Once the block is validated, it becomes part of the network's accountable and unchangeable blockchain. Furthermore, a built-in defense mechanism is present. In particular, the blockchain will "defend" and capture any malicious contamination it finds (such as attempts to alter any hash code of all the blocks). It will also rectify the corrupted block on the infected node.

This article seeks to thoroughly investigate and analyze the impact of BCT on shifting the food supply chain with principles of circular economy and sustainability. By combining current research, real-life examples, and practical applications, the goal is to offer an in-depth knowledge on how blockchain can improve traceability, transparency, and accountability in the food sector, resulting in a more durable and sustainable worldwide food supply chain.

This analysis provides a comprehensive assessment of BCT's influence on the whole food supply chain, from production and processing to transportation and consumption. The study includes research, review publications, and case studies that emphasize the use of blockchain to solve food-related concerns such as traceability, transparency, and sustainability. The inclusion criteria prioritize the information's significance, trustworthiness, and usefulness to the overall issue of circular economy and food supply chain integrity. To provide a full summary, a systematic literature review process will be used. This will include finding and analyzing peer-reviewed research and review articles, as well as relevant reports from reputed databases (Scopus and Google Scholar). The analysis will concentrate on major issues, techniques, and study findings, allowing for a synthesis of many viewpoints on BCT in the food industry. Real-world case studies and projects will also be studied to give practical insights into how blockchain solutions may be successfully implemented.

The review is divided into various parts to aid in gaining systematic knowledge of the topic. The first part presents an overview of the global agronomic supply chain difficulties and the significance of blockchain as a disruptive technique. The study then goes into particular blockchain applications for improving traceability, transparency, and accountability in the food supply chain. The topic then broadens to look at how blockchain supports circular economy activities and adds to overall sustainability. Real-world case studies are used throughout to demonstrate effective implementation. The report finishes with a summary of results, identification of problems, and suggestions for future research and industry practices.

2 Methodology

This evaluation was carried out utilizing around fifty-eight research and review articles on BCT in the food supply chain and its sustainability. Extensive literature reports were compiled by searching the titles and abstracts on Scopus and Google Scholar for keywords such as blockchain technology, food supply chain, circular economy, sustainability, transparency, traceability, food fraud, provenance, decentralized ledger, smart contracts, IoT, case studies, and so on. These papers have been incorporated in order to demonstrate BCT and prospective applications. The research articles and reviews using data handling were selected from reputed publishers included in Journal Citation Reports (JCR).

3 Blockchain technology (BCT)

3.1 BCT characteristics

BCT has several features to run a smooth and sustainable food supply chain, which is presented in Fig. 1 and are listed below.

- Decentralization: The system's data can be viewed, tracked, saved, and updated on a number of different systems.
- Transparent: With web's consent, data are gathered, saved, and retrieved on the networks. Additionally, it is always traceable and visible.
- Immutable: To confirm immutability, BCT offers timestamps and controls.
- Irreversible: An individual blockchain keeps a detailed and certifiable record of each transaction.
- Autonomy: Without a third party's assistance, any blockchain node may autonomously acquire, send, save, and update the data.
- Open source: Every member of the network has open-source access through blockchain while still retaining a hierarchy.
- Anonymity: The person's identity is kept secret when records are sent among nodes.
- Ownership and individuality: Each document shared on the blockchain keeps a record of its own transactions and a distinct hash code.

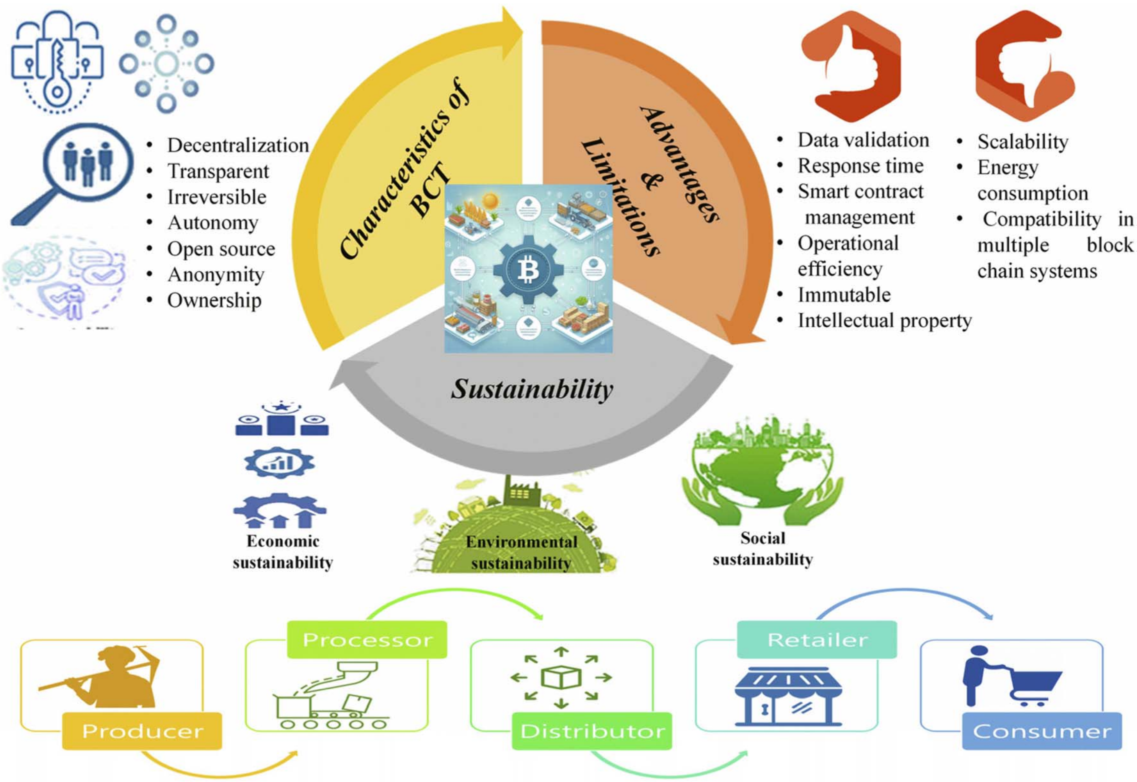

Fig. 1 Block chain technology in food supply: characteristics, sustainability, and advantages and limitations presented in the form of figures and also in text format, showing in a systematic way the advantages, disadvantages and members of the food supply chain.

• Provenance: Each product in the blockchain has a digital record document that attests to its legitimacy and place of origin.

• Smart contracting: Often known as contract automation, it is a straightforward piece of computer software that facilitates contract execution. There is no need for a contract because of improved security and cheaper transaction costs. The rules, penalties, and procedures which will be enforced on all participants in the transaction are often put into smart contracts. Supply networks benefit from smart contracting's rapid response capabilities.[13]

3.2 Advantages and limitations of BCT in supply chains

There are various advantages to implementing BCT in the food supply chain (Fig. 1). (1) It allows validation of data situated across multiple supply chains, which increases the security of data and real-time recording of all information in data management. Furthermore, blockchain enhances transparency and aids in the tracking of a product's state throughout a procedure, automating data analysis tasks, and enabling end-to-end transparency depending upon the authorization level through order. (2) Expands response spell, resulting in a dynamic and real-time supply chain with greater resource employment. (3) Smart contract management allows for customized and specific agreements to be formed for every task and organized with one another, which aids in the planning of business processes, enhances visibility, and removes the need for an intermediate. (4) Operational efficiency enhances the end-to-end efficiency of the supply chain workflow and discovers flaws and difficulties early on to ensure the process's robustness. (5) Disintermediation results in a continuous chain of transactions with greater speed and confidence between business parties. (6) Immutability establishes a consensus approach for all supply chain alterations and protects the privacy of all transactions. (7) Protection and registration of intellectual property.[14]

In food supply system, block chain technology provides an accountability which increases customer trust and aids in the fight against food scams. Furthermore, real-time moisture and temperature surveillance during transit might improve food safety and quality. Despite its promise, the adoption of BCT is fraught with difficulties (Fig. 1). Scalability and consumption of energy are still concerns that must be addressed. Furthermore, compatibility across multiple blockchain systems and current infrastructure presents challenges. The IBM Food Trust network, which intends to develop a standardized system for the food sector while promoting interoperability, is one example of solving these difficulties.

3.3 Different blockchain types

Blockchain is separated into three types: public blockchain (also known as the "public blockchain"), consortium blockchain (also known as the "consortium chain"), and private blockchain (sometimes known as the "private chain").[15] The

Table 1 Analysis of different categories of blockchains

Category	Features	Use	Users	Challenges
Public blockchain	Every public peer gets equivalent access to rights like reading, writing, and performing. The records are available to everyone, and the public peers may access the blockchain privately	Monetary like bitcoin	The public node is open to all users	As the transaction volume increases, there arises a need for more storage and computational demands, and increased throughputs expose the network to attacks, compromising security
Consortium blockchain	The accessibility management policy has to be followed for each operation. Authentic identification and data audits are supported by the organization's blockchain	Institutional organizations like: academic institutes, medical institutes research organization, *etc.*	Membership in the alliance P2P blockchain networks is restricted to those who are authorized	Interoperability is a challenge due to customized protocols
Private blockchain	The private node is the only one with access to the behavior. Limited utilization value, strict safety standards, and private rights	Banks, finance industries, *etc.*	The blockchain is only accessible by approved private peers, such as businesses or organizations	It is vulnerable to tampering as operators can also alter or censor data due to lack of decentralized incentives

characteristics, target markets, and variety of applications for different blockchain variants are listed in Table 1.

3.3.1 Public blockchain. Anyone or any organization in the Internet is welcome to join the public blockchain system, which is known as a public blockchain. Since any network user can contribute to the transaction validation, this method is entirely distributed and censorship-resistant. In the open blockchain network, every user can participate in the consensus procedure.[15]

3.3.2 Consortium chain. The member nodes of the system are predetermined by a particular criterion in order to identify and confirm each node's identification in a consortium chain, which uses a number of co(partial decentralization) structures. Through the alliance chain, the control authority of the nodes is easily set.[16]

3.3.3 Private chain. Despite having a limited degree of decentralization, private chains are nonetheless widely used. The members who are permitted to participate and verify transactions are defined by the central controller.[15]

4 Food supply chain

The food supply chain is a complex network involving producers, processors, distributors, and merchants. Challenges include transparency, traceability, and food safety. Traditional methods struggle to provide real-time information, leading to inefficiencies and risks. BCT offers a secure, transparent, and decentralized platform for recording and sharing information across the chain. The crucial steps that make up a typical agri-food supply chain are described below.

4.1 Production

All of the fundamental agricultural tasks completed on the farm are included in the production phase. To raise crops and cattle, the farmer uses unprocessed, organic elements (fertilizers, seeds, animal breeds, and feed). Depending on the cycle of farming and animal production, they will have one or many harvests or yields throughout the year.

4.2 Processing

In this stage, a main product is completely or partially changed into one or more secondary products. The secondary products are then often packaged, with each receiving a code that can be used to identify it specifically and which comprises information such as the manufacturing date, list of raw materials used, *etc.*

4.3 Distribution

The product is made available for distribution after it has been packaged and labelled. There can also be a requirement for a storage phase in between, depending on the product and the delivery period.

4.4 Retailing

Following distribution, the products are sent to retailers who then sell them to the final consumer in the food chain. In this case, the end user will be a customer who buys the product.

4.5 Consumption

The final link in the supply chain, the client, purchases the item and asks for verifiable information about the product's quality requirements, country of origin, manufacturing procedures, *etc.*[17]

The main actors and different phases of the food supply chain are depicted in Fig. 1. This system is unreliable and inefficient.[18] The settlement processes for the trade of goods are intricate and paper-intensive. These procedures are opaque and involve significant risks for both buyers and sellers when money is exchanged. Due to the vulnerability of transactions to fraud, middlemen become involved, raising the overall cost of the transfers.[19] The cost of running supply networks is thought to account for two-thirds of the total cost of commodities. As a result, there is plenty of room for supply chain optimization through efficient operating cost reduction. Finally, when consumers shop locally, they are uninformed of the sources of the products or the environmental impact of the manufacturing process.

Traditional methods of managing the food supply chain often lack real-time visibility throughout the supply chain, which may make tracing the origin and transit of items challenging. Paper records are readily lost or manipulated. Centralized databases are subject to hacking and unauthorized access, putting their confidentiality at risk. Consumers frequently have no confidence in the knowledge offered by middlemen, raising worries about the legitimacy and quality of products. Manual documentation, data input, and interaction with stakeholders may all result in delays, inaccuracies, and higher operating expenses. Traditional approaches for determining the source of contamination in the event of a product recall depend on time-consuming inspections. In contrast, BCT, recognized for its transparency and consistency, presents a revolutionary solution to these problems. Every stage of the supply chain is immutable and transparently documented. Participants may have real-time knowledge about the product's route, which improves traceability and openness. Data are encrypted and distributed throughout a decentralized system, making them almost hard to edit or control. This verifies its correctness and legitimacy. Consumers may have easy access to trustworthy data about the origin, ingredients, and certifications of a product, increasing confidence and minimizing dependency on middlemen. Smart agreements, automated data gathering, and real-time updates expedite procedures, minimizing documentation and enhancing the overall efficiency. Rapid and exact traceability allows for immediate recognition of the source, allowing for targeted recalls and reducing the effect on customers and the industry.[14]

5 Traceability

5.1 What traceability means

Although, there are many definitions of "traceability" to be found in dictionaries of ISO 8402, ISO 9000, ISO 22005, the EU General Food Law, and other sources, most of them have shortcomings.[20] The definition of traceability is changed by eliminating the words "trace" and "track" and replacing them with "traceability systems" and "recorded identifications" in order to provide people in the supply chain with details about the origin, components, and locations of the products. Sarpong (2014) stated that while assessing the problems with cooperation and traceability in the supply chain, accountable persons should identify acceptable long-term goals and send the pertinent information to the traceability system in order to gain favorable results.[21] A traceability system is crucial for tracking products throughout the supply chain. "Totality of data and activities that may maintain required details about the produce and its components across all or a portion of the chain of production and usage" is what the ISO defines as a blockchain system.[22]

5.2 Need for traceability

As markets become increasingly globalized, there are greater international transfers of goods, information, and people. The availability of food items from different regions of the world in local markets benefits consumers. Additionally, purchasing fruits and vegetables out of season is generally seen as "normal". On the other hand, the difficulty of ensuring food safety has also been brought on by the globalization of the food industry, due to the fact that food supply systems are becoming increasingly integrated and dependent on more players. In a perfect world, quality assurance calls for complete traceability of every component of the finished product. To meet consumers' growing needs for safety, quality, and sustainability, this requirement necessitates the transmission of high-quality information between all parties. More stringent national and international legislation, as well as tighter controls over food safety and quality, were also brought about by the several food crises that occurred in the 1990s and 2000s.[23–25] In 2008, the melamine milk powder incident in China is a well-known illustration of a food scandal that had devastating results.[26] In this incident, the newborn milk powder tainted with melamine is known to have killed at least six babies. The sector suffered a decrease, and as a result business officials were detained, and the company that supplied the contaminated newborn milk powder filed for bankruptcy. Regulatory outlines among nations and regions differ greatly, and food safety matter and disaster scenarios continue to often arise on a worldwide scale despite greater attempts to regulate the necessary food control procedures.[27] For instance, the New York Times website returns three articles regarding this subject per month when the keyword "food safety" is entered. Incidents and crises involving food safety have not only prompted regulatory action but also raised consumer awareness. Food traceability is currently viewed as a crucial component in maintaining the product's quality and safety in the food industry, which boosts consumer confidence and satisfaction.[28,29]

5.3 Conceptual framework of traceability

The theoretical outline created by Aung and Chang were used to relate various notions as well as qualities of food traceability to the other players in the food supply chain for our study (Fig. 2).[30] The journey from origin (for example from a farmer on a farm) to the final commodity that a consumer purchases and consumes at a store is defined by their paradigm's supply chain, which is made up of multiple players. Traceability throughout the whole chain of players becomes practicable *via* interior and exterior traceability. The fundamental principle of the framework is that everybody involved in the food supply chain must utilize different types of technology to submit data into and receive information from the Food Safety Information System (FSIS). The FSIS provides a variety of data kinds which are important for the actors in the food supply chain to ensure

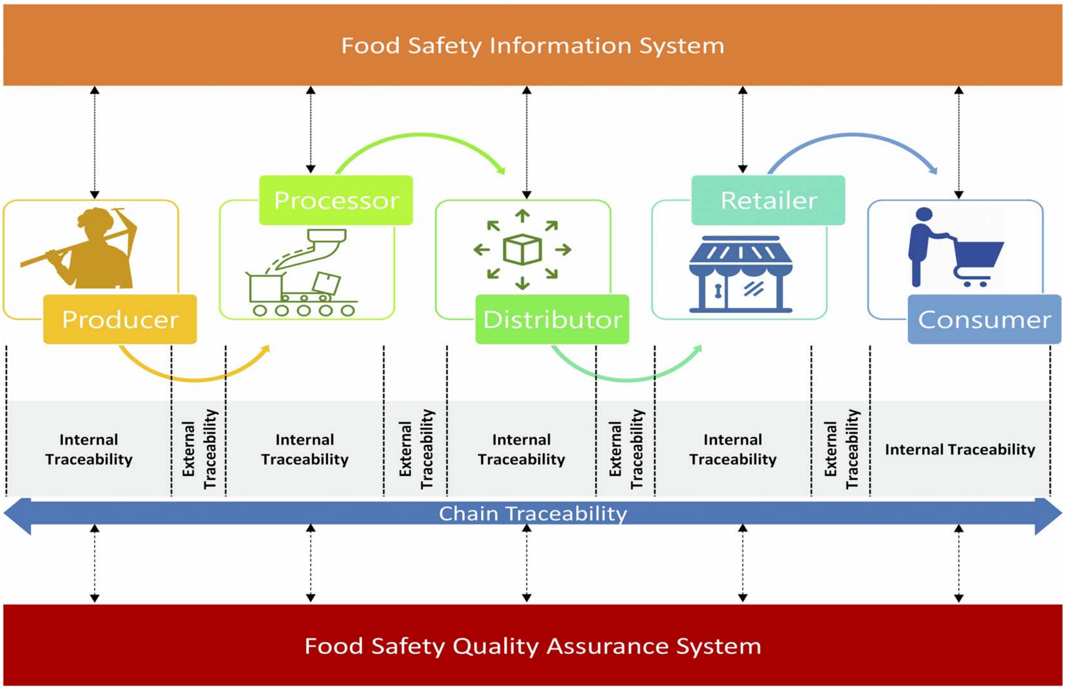

Fig. 2 Conceptual framework of traceability.

transparency and quality assurance. Aung and Chang do not define whether the FSIS is a centralized information system or a dispersed information system.[30] It is crucial that all actors have simultaneous access to the same data. The Food Safety & Quality Assurance System (FSQAS) provides the safety and quality standards that the supply chain participants must adhere to traceable information, confirming adherence to these criteria provided by the FSIS. The supply chains for food products will be described in particular using the following traceability system components:

5.3.1 Business context. From the farm to the customer as well as every step in between, the clientele, product markets, and ingredient types all have an impact.

5.3.2 Supply chain. Variations in the supply chain, such as the number of suppliers, the features of the manufacturing procedure, packing, and the storage and distribution process, determine the complexity of the traceability process.

5.3.3 Regulation. Internal quality management systems must acknowledge appropriate food safety and quality standards that may be nation or product specific.

5.3.4 Quality. Applied technologies make it simpler for a system to record the outcomes of quality testing of product and process attributes (as well as traceability information).

5.3.5 Traceability information system. The traceability information system, which acts as a platform for data sharing, is accessible to all stakeholders. Global standards for data exchange technology should be utilized to ensure compatibility.

6 Application of BCT

Since its introduction in 2008, BCT has been considered an asset that fosters trust between stakeholders while providing a variety of advantages.[13,31] BCT, with its safe, clear, and decentralized properties, presents an interesting application opportunity for invention in a variety of sectors. Its uses have mainly developed with technical developments and greater interest from multinational businesses.[32] It was initially designed to keep financial transactions among people, and its uses had mostly shifted with developments in technology and greater demand as of multinational businesses. At the moment, a rising number of agencies and organizations throughout the globe are devoting greater efforts to study this sector. Table 2 depicts the usage of BCT in associated sectors such as, supply chain, education, finance, agriculture, internet, health and medicine, government, and others. Some of them are still in the testing stage, while others are now in use.

6.1 Application potential for BCT in plant food safety control

Agronomic practices include the phases of seed procurement, growth, watching them develop, harvesting them, transferring them, storing them, and selling them in the process of taking plant food from the field to the consumer's plate. The safety and quality of food are significantly impacted by each of these connections. The process starts with the seed purchase. The type of seeds used determines the genetically modified food. Many consumers continue to be skeptical of genetically modified food at this time.[14] They are entitled to know what kind of food they are purchasing. As a result, records of seed purchases and variety information must be written down. Environmental pollution is getting worse with industry growth, especially in developing nations like China, Brazil, India, and Russia. Developing countries frequently disregard how industrial expansion harms the environment, particularly water contamination and soil contamination, which have

Table 2 Related applications of blockchain[a]

Application field	Key directions
Insurance	Mutual insurance, *etc.*
Supply chain	Supply chain management, *etc.*
Education	Academic management and learning achievements, *etc.*
Financial	Cryptographic currency, digital financial transaction, *etc.*
Agriculture	Agricultural supply chain management, *etc.*
Internet	Network security management, certification, *etc.*
Health and medicine	Electronic medical record, drug counterfeiting, *etc.*
Banking	Cross-border payment, money transfer, *etc.*
Government	Citizenship identification, *etc.*
Others	Copyright, energy, *etc.*

[a] Table adopted from Xu *et al.* (2020).[14]

turned into covert threats to food safety, in favor of concentrating primarily on economic development. The biggest issues with plant food safety are pesticides and heavy metal contaminants. Most contamination by heavy metals in food happens during the planting phase. Polluted environment, water, and soil are prone to generate a considerable amount of residual of dangerous chemicals on plants. It is crucial to confirm the soil's heavy metal content, pesticide pollution, water quality, and air quality before planting. The Fukushima Daiichi nuclear disaster, the greatest nuclear leakage ever to happen at a nuclear power station, occurred in 2011 and caused varied degrees of nuclear pollution in neighboring nations and regions.[14] Therefore, it is necessary to document information about the geographic areas where crops are grown, particularly latitude and longitude, the amount of annual sunshine, and the amount of annual precipitation. Pesticides must be employed during the cultivation process to guarantee the high quality and high output of plant food. To increase crop income, some farmers may use pesticides against the advice of experts or avoid the disintegration period altogether. Because pesticides are not broken down, there are too many pesticide residues in plant food, which are harmful to human health. The certification of product grades in China is impacted by the use of fertilizers and pesticides.[33] The presence of insect pests is influenced by the climatic environment, which also has an impact on how pesticides are used. As a result, information about agricultural pest and disease monitoring must also be kept in the file. Crops have a growth cycle, and the finest quality is produced when harvesting at the correct moment. The freshness and sugar-to-acid ratio of fruits and vegetables are dependent on the timing of the harvest. Even after being harvested, plants continue to breathe. As a result, following harvest, the quality of plant food is also greatly influenced by the atmospheric moisture, temperature, and oxygen content in the storing, shipment, and transportation environments. These elements have an influence on the quality and security of plant food, so plant food quality and safety may be managed at the source utilizing BCT. The data on water, soil, and environmental conditions, along with information about vegetable varieties, manufacturing processes, and the supply of various farming resources such as insecticides, weedkillers, and manures, is essential for effective agricultural management. Farmer resources in different regions, are all transmitted *via* multiple platforms (government websites, non-government organizations, and social media).[34] The network's nodes can utilize a "consensus technique" to verify every associated transaction (acquisition and application of seeds, insecticides, weedkillers, and fertilizers) connected to farming.[35] The following is its basic tenet. In a peer-to-peer (P2P) system, each node initially confirms each transaction that joins it. The transaction is confirmed by the nodes if they concur that it is legitimate. This new block is permanently locked and added to the old blockchain.[36] Consumers can better understand the things they purchase by adding the origin details to the blockchain. Every transaction is further disclosed to every member to search for any unexpected transactions prior ending automatically in line with the intelligent agreement's rules. Employing the application of insecticides as a case study, the consortium's BCT setup in the food industry enables every container of insecticide goods to be identified by only one verification and can only be sold once to a single address (account) same or a different address (account); this hinders the buying and selling of insecticides in contravention of the law.[37] The blockchain also maintains other useful data, including the number of pesticide manufacturers in a particular area, the cost of ingredients, and the yearly output of insecticides of each company.[36] The blockchain's consensus method provides the ability to perform simultaneous verification of certain data. The majority of insecticides can only be legitimately used by licensed and registered producers, and personal data of insecticide users are additionally entered into the blockchain.[38] Since payment data for purchasing insecticides is uploaded to the blockchain and cannot be manipulated, this immutable record can be used to identify whether a farmer is using pesticides illegally.[39] Similar to this, with plant foods, crucial information is put up in the smart contracts prior to planting. The legal restrictions and agreement conditions of the computer language code serve as a record of a contract's terms in the blockchain system. Smart contracts eliminate intermediaries and lower the transaction, contracting, execution, and compliance costs since they are self-enforcing and tamper-resistant. Other advantages include the cost-effectiveness of low-value transactions, the interoperability of transaction systems, and the capacity to enforce smart contracts on blockchains to make sure producers adhere to the requirements. The smart contract is instantly cancelled and the validated data cannot be added to the blockchain system when it conflicts with the smart contract. As a result, the blockchain can not only increase the authenticity and transparency of information about food safety and quality but also boost consumer confidence and buy intent.[14]

6.2 Application potential of BCT in animal food safety monitoring

Animal food quality and safety are essential worldwide problems.[40] Veterinarian leftovers, hormonal and antibiotic residuals, zoonosis, adulteration of meat, harmful microbiological contamination, risks from feed with pesticide or herbicide residues, heavy metal residues, and various other pollutants are the primary causes of animal food safety and quality challenges.[41] From farm to table, the animal food chain includes feeding, distributing, slaughtering, dividing, and retailing. Fig. 3 illustrates how BCT is being used to monitor the safety of animal food.

Diseases and the use of veterinarian medicines will undoubtedly interfere with animals while they are being fed, leaving veterinary pharmaceutical residues.[42] Besides, feed and the quality of feed have a significant impact on how safe the meal is for animals. Additionally, if the animals are in a free-range or grazing mode, dynamic monitoring of numerous environmental pollutants (including heavy metals and organic pollutants) is necessary. Animals who consume contaminated water get sick and require antibiotics to recover from their illnesses. As a result, throughout the feeding process, it is crucial to ensure the safety of drinking water in addition to the feed. The temperature plays a significant role in determining the safety of animal feed at all stages of meat manufacture, from farm to fork. The health of the animal is influenced by the temperature of the feeding environment. For the animal's health to be protected from significant temperature changes, it should be kept in a dynamic balance. Animals must be taken to a specified location for slaughter when they are released from captivity. The temperature has an impact on the animals' physiological status during this phase as well. After livestock has been killed, meat products are typically contaminated by microbes.[43] Microorganisms are born when conditions are aberrant, which affects the quality of meat and poses a threat to food safety.[44] The major goal of managing ambient temperature is to manage microbial contamination of meat products. The final color of animal food is influenced by the ambient temperature in the relevant area of the animal body. Thus, it is vital to maintain an eye on the temperature throughout every step of making animal food. The 2013 horse meat incident and the 2016 annual report of the EU Food Fraud Network reveal that adulteration of meat-based products is frequently reported in the EU event databases.[45,46] The Rapid Alert System for Food and Feed (RASFF) database, an extensive system developed to ensure the security of animal food and animal feed in the EU, was established by the European Union to address the problem of contaminated meat.[47] The inclusion of prohibited colors or other compounds, as well as an excess of vitamins and metals, fall within the RASFF composition category (such as aluminum). There is no mechanism to detect information

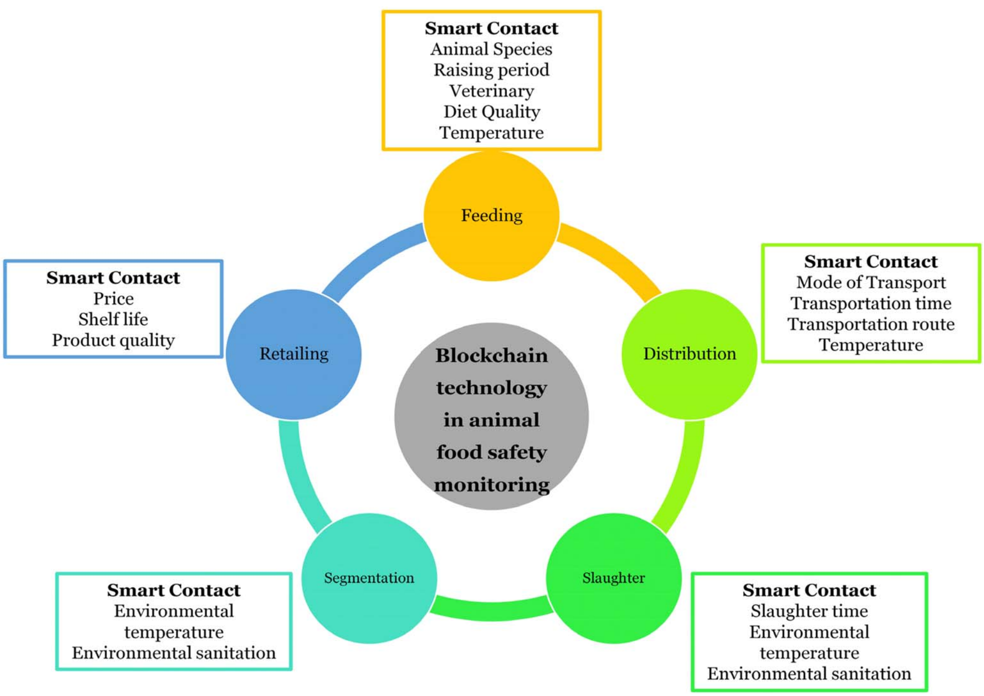

Fig. 3 Application potential of blockchain technology in animal food safety monitoring.

adulteration or tampering in this database. When using BCT to produce animal food, we can get the most original information since once it is recorded into the blockchain system, it cannot be changed. In the blockchain system, the flow of animal food manufacturing might be digitally monitored in an unchangeable atmosphere. The ambient temperature is continuously monitored by an ambient sensor, from animal breeding through retail, and relayed to the BCT.[48] The temperature data are compared by the smart contract with numerous legal standards. The product is made available if the requirements are met. The transmitter and recipient receive a deviation notification if the temperature and other tracking circumstances considerably differ from the statutory necessities. The transaction terminates, the smart contract expires automatically, no illicit meat products are sold, and the meat products' microbiological safety is ensured.[49] The species and number of animals raised by growers are likewise documented in the blockchain system, as are the manufacture and sale of veterinary medications, antibiotics, or feed. The smart contract immediately cancels the transaction if the farmer uses an uneven amount of veterinary drugs or antibiotics, which happens when a farmer uses veterinary drugs or antibiotics illegally because the information in the blockchain is perhaps simultaneously checked. The blockchain system does not save the data. Genetic analysis and near-infrared imaging are employed to identify species or varieties after the animal has been killed.[50,51] The blockchain system, which confirms the meat's authenticity, receives this information as RFID tags or QR codes. Therefore, the use of BCT can be used to stop meat adulteration at its source.[14]

6.3 Potential application of BCT for processed food safety regulation

Along with the critical components of plant and animal food safety and quality control, concerns about processed food processing safety and quality control are raised. As previously stated, a blockchain is a digital transaction log managed by a network of various computer units that are not dependent on an impartial party. Fig. 4 shows how processed commodities must go through a variety of phases before being sold to consumers, including sorting and retailing. As a result, each block in Fig. 4 represents a separate transaction data file that is handled by specialized programs that enable the data to be sent out, handled, saved, and rendered in a human readable format. Each of the blocks in its original electronic form has a header with a time-stamp, containing a piece of transaction information recorded in each block in a blockchain as a distinct serial number, and a link to the preceding block. Once filled out, the data are encrypted using a process that generates a hexadecimal number known as hash. Each block generates a hash depending on its contents, which is then referenced in the next block's header (Fig. 4). Thus, any tampering of a particular block would result in a discrepancy in the hashes of all subsequent blocks.

6.3.1 Sorting. Before entering the factory, the raw materials must have the appropriate quality certificate. Generally speaking, food manufacturers sort the raw materials and remove unqualified components, such as rotten fruits and vegetables, to maximize the added value of the meal. In order to ensure food safety and quality, this process must be carefully controlled. Consequently, this process calls for knowledgeable personnel or delicate machinery.[52]

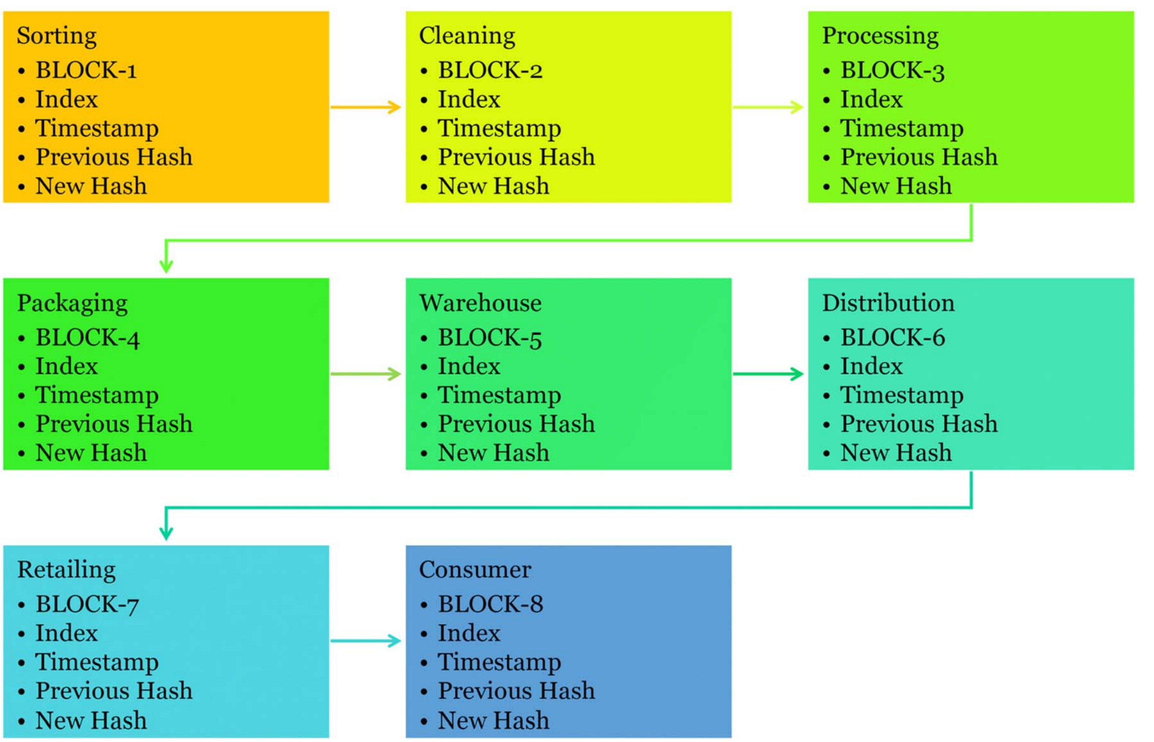

Fig. 4 Blockchain technology's potential applications for processed food safety regulation.

6.3.2 Cleaning. This method is intended to eliminate pollutants like soil, blood, and bacteria that persist on the surface of plants or animals. For this procedure, a cleaning-in-place method might be utilized. The related sanitary inspection is carried out when the cleaning procedure is finished. The HACCP protocol states that the test findings are automatically and directly synchronized with the blockchain system. The test results enter the processing process if they are in compliance with the pertinent standards. The production process is stopped if the outcomes don't satisfy the pertinent requirements.[53]

6.3.3 Processing. There are various methods used to process various foods. Cutting, heating, dehydrating, drying, adding additives, *etc.* are a few common practices. The overall quality of the meal is impacted by a number of factors during these fundamental processes, including water content, temperature, and time. In this step, there are IoT-based wireless sensor networks that are incharge of checking various metrics (moisture, temperature, and time). Direct transmission and summarization of the data collected by the wireless network sensor into the blockchain system occur in the process. The pertinent data are encoded by the hash algorithm once the processing parameters have been uploaded to the blockchain system, and they cannot be modified later.

6.3.4 Packaging. To reduce late microbial infection, processed food must be packaged. Critical factors in the packaging process include the packaging shop's cleanliness and temperature.[53] A thermometer can be used to determine the temperature characteristics of the packaging store. Food science can use DNA analysis to address a variety of demands (microbial determination).

6.3.5 Distribution and warehousing. The steps of distribution and storage are fairly expensive and complex. The main elements determining food safety and quality are the temperature, gas composition, and cleanliness of the storage and distribution environment. The real-time distribution and storage of environmental data are monitored by the IoT-based wireless sensor network equipment, and they are timely submitted to the blockchain system. When data transfers in blockchain systems reach predetermined limits, smart contracts immediately stop them. Additionally, a logistic center can use Global Position Service technology to implement vehicle aligning for every vehicle and optimize its direction by analyzing and recognizing traffic circumstances to reduce delivery times.

6.3.6 Retailing. When retailers receive the processed product, they learn everything there is to know about the food's manufacture. Then, when purchasing, customers can use an RFID reader or a QR code to get all the information, including the manufacturing address, method, key pointers, manufacturing time, and shelf-life. In parallel, the blockchain technology system automatically collects all relevant data regarding the meal and compares it with the data gathered from customers.[54] The meal is a fraudulent product if the information differs from what the blockchain records. For tracking food production, a distributed information system has been developed that draws on HACCP, BCT, and the IoT. In this system, BCT may regulate every step of the food manufacturing process, including sorting, cleaning, processing, storing, moving, and selling. In developing nations, producers typically combine inexpensive ingredients that are unhealthy for people to increase profits; purposeful deception is extremely widespread at the expense of the food quality for sale. The data of each connection are uploaded into the blockchain system when BCT applies for processing goods. These data involve: (1) the processing atmosphere, such as temperature, humidity, and machinery sterilization; (2) the application of suitable additives; (3) essential data on processing facilities as well as associated staff members; and (4) data concerning transportation and storage, such as amount, class, temperature, humidity, and storage conditions.[55] These data are entered and updated on the blockchain in real-time before a consensus is formed. Once an agreement is formed, they become irreversible, ensuring the accuracy of food information.[14]

6.4 Blockchain-driven transparency for sustainable food supply chain

BCT promotes consumer demand for sustainable products by increasing transparency and traceability. BCT enables rapid access to data regarding sourcing of the raw material, processing methods, and transportation. A recent study demonstrated the effectiveness of an AI-blockchain integrated model for traceability of halal food products. The model used quick response (QR) codes generated using convolutional neural networks (CNN), which allowed the users to trace a product's journey through the supply chain.[56] This form of transparency enables the verification of claims like “organic” or “sustainable”. This is because it provides full information regarding the raw material sourcing, production method or farming practices, and amount of carbon footprint generated.[57] As consumers increasingly prioritize sustainable practices, demand ethical and environment-friendly goods, integration of BCT into the food industry helps in enhancing the integrity in the supply chain, which in turn helps build consumer trust.

7 Case study

7.1 Dairy case study

The four supply chain processes were chosen based on the variety of products and processes, which affect regulatory demands and are anticipated to fulfil various boundary conditions.[57] This will allow for the identification of boundary parameters that represent a number of distinct scenarios. The following five criteria were used to analyze these cases: business, supply chain process, regulation, quality assurance, and traceability processes listed in that order. A summary of the individual four supply chains can be found in Table 3.

Milk is processed in the dairy essential supply chain to create premium cheese, butter, and milk powder. The process is highly standardized, with varying ripening times, external ripening locations, and cheese uses. Whey, a by-product, is a significant component. Quality control and standardized regulations are in

Table 3 Food supply chain in the dairy industry[a]

Element	Dairy essential	Dairy consumer	Dairy special	Dairy ingredients
Business	• Hard cheese, butter, milk (powder) • B2B/B2C market • Main supplier for 'Ingredients'	• Country-specific branded products • B2C market • Large variety of products	• Products for special target groups (*e.g.* baby) • B2C market	• B2B market, often based on specs of customer • Large variety of different suppliers specialized production process
Supply chain process	• Raw milk as an ingredient • Small number of ingredients • Standardized production process • Hard cheese requires an extra step • (Ripening)	• Raw milk as an ingredient • Large number of different ingredients • High variance in production processes • Packaging important at the end of production process	• Short production process • Packaging important at the end of production process	• Mass production process as well as customer specific processes • Technology driven • Delivery in big bags
Regulation	• Food Safety System Certification (FSSC) 22 000 applicable to all products • HACCP principles • Products for particular countries might need to comply with specific regulations • Generic traceability requirements ('one step back, one step forward' principle)			
Quality assurance	• Compliance with internal quality standard • No quality sampling by customer • HACCP implementation	• Compliance with internal quality standard No quality sampling by customer • HACCP implementation	• Compliance with internal quality • Standard + extra requirements • No quality sampling by customer • HACCP implementation	• Compliance with internal quality standard • Production process certified by customer • HACCP implementation
Traceability	• Demand based on regulation from customer • Level of traceability dependent on granularity of production batches and backflush of ingredients	• Increasing demand from consumer; demand based on regulation from customer	• High demand from consumers	• Additional requirements from customer

[a] Table adopted from Behnke and Janssen (2020).[57]

place to ensure the quality of these products.[57] The dairy consumer supply chain involves various production steps and supplies goods for the B2C market (Table 3). The packaging of finished products involves various procedures and additional suppliers and customers. Standardized regulations and quality control are in place, with specialized products subject to additional quality and traceability standards. This includes biological products, which require additional nutrition for the cow and the supply chain process.[57] The dairy ingredient supply chain, catering to the B2B sector, relies on specialized production techniques and requires customers to request independent certifications. Additional regulatory criteria may apply for medical ingredients, and traceability standards may be required.[57] The dairy special supply chain focuses on producing goods for specific consumer demographics, such as infants, sports, and the elderly (Table 3). The production process involves combining materials, but additional quality controls are necessary due to unique consumer groups and regulatory obligations. Regulation-driven traceability requirements are similar to other supply chain operations. An initiative aims to increase consumer openness about component types and sources, requiring a higher degree of traceability. This conceptual framework's understanding of the supply chain served as the foundation for an analysis of the boundary conditions and the applicability of BCT as a food safety information system.[57]

7.2 Walmart case study

7.2.1 Lowering the risk to food safety. Reducing food safety concerns is the first advantage of using blockchain in Walmart's supply chain. For instance, Walmart, the biggest retailer in the world, views China, the nation with the greatest population, as having a sizable prospective market. The Walmart brand, however, was severely damaged by food contamination incidents like the 2014 tainted donkey meat disaster and the 2011 pork mislabeling scandal.[22] Nearly 1 in 10 individuals get sick from eating contaminated food, according to the World Health Organization.[22] Unsafe food is said to include "harmful bacteria, viruses, parasites, or chemical compounds". However, it is anticipated that blockchain will have a favorable effect on food traceability in Walmart's supply chain. The supply chain is "tracked" and "traced" in both directions through traceability.[58] Food may now be traced digitally from the farm to the store, making it possible to plainly depict an individual item's life course. In addition, food may be tracked from the shelves to the farm, enabling Walmart to quickly identify the sources of foodborne diseases in the event of an outbreak.[22] This improves pollution management as a result. To some extent, this aids Walmart in assessing health risks at every level of its operations and saving lives at the start of an outbreak. Furthermore, Walmart does not need to take away the same categories of allegedly affected goods off the shelves. Recalling the precise batch of contaminated food is the only need. As a result, the financial impact of food recalls on Walmart can be greatly diminished. Through the whole supply chain, BCT improves information sharing in a safe environment. Everyone can access the data recorded on the public blockchain, and it cannot be altered. As a result, it improves the food supply chain at Walmart in terms of confidence, security, and transparency. Consumers' confidence is increased because they can obtain more precise tracking information about their food through their smartphones. The head of food safety at Walmart, Mr. Yiannas, asserts that despite the possibility of data being altered, paper records continue to rule the food industry. However, as papers are converted to digital form and parties' data are recorded on the blockchain, less requirement exists for human data management. Because no one can alter the data history, human error may be limited and the likelihood of corruption can be decreased, which should prevent food fraud. Additionally, BCT is a strong tool for regulators to assist Walmart in examining its food supply chain and making the roles of all parties more evident in light of immutable data.[22]

7.2.2 Enhancing supply chain efficiency. The food supply chain of Walmart could become more efficient, thanks to BCT, whether in terms of food flow, information flow, or financial flow. Walmart can collect real-time data to monitor the growing, producing, processing, and marketing of food because blockchain enables real-time accessibility. Consequently, it is possible to check the food's origin and quality at any time. For instance, whether it is still in logistics or has already been placed on the shelves, Walmart can detect any food that has been improperly handled or that has expired before it reaches consumers. According to Walmart's 2018 Global Responsibility Report, the company wants to reduce and even get rid of food waste from its operations by 2025. It plans to do this in Canada, Japan, the UK, and the US. Food waste continues to occur at all levels, including in the logistics process, stores, and distribution centers. By determining the ideal delivery schedule and shortening the delivery time for perishable food, BCT will help Walmart eliminate the problem of food spoiling and cut down on food waste and costs. Last but not least, IBM Global Finance offers Walmart blockchain and smart contract solutions to assist with dynamic inventory and price management.[22]

7.2.3 Increasing cooperation. The food supply chain for Walmart spans numerous borders and has millions of suppliers worldwide. But, through the shared ledger, BCT is anticipated to manage the intricate relationships in the supply chain. Additionally, the Walmart and IBM seek to solve food safety issues in collaborative settings rather than *via* rivalry by adopting blockchain-based experiments, seeing the food system as a comprehensive system for everyone in the world. For instance, IBM Food Trust solutions are working to connect Walmart and other participants in a seamless manner, demonstrating the stakeholders' constructive attitude toward cooperating and building a community of interests. As a result, implementing BCT is the best approach for Walmart to enhance cooperation in the food business and reap the benefits of strategic alliances.[22]

7.2.4 Discussion. Because the technical processes rely on already-existing technologies, including RFID and sensors, yet face significant coordination challenges, adoption of blockchain in the food supply chain appears to be in a substitute stage. Given that Walmart has incorporated BCT into its food supply chain, it is logical to assume that the retailer is pursuing the first mover advantage in accordance with the Shi and Chan's strategic framework.[59] By embracing technology, Walmart might strengthen its hegemonic position in the food supply chain. Evidence suggests that Walmart improved food traceability by integrating BCT into their supply chain from 6–7 days to 2 seconds.[60] However, the firm may encounter significant challenges due to high adoption costs for BCT. In addition, only when all partners in the supply chain participate there are significant benefits. Therefore, cooperation is a way for the parties involved to come to a win–win situation in the near future. To prevent the situation where the technology is only used by the focal corporation, Walmart may have to "push" its unwilling supply chain partners to adopt and use BCT because perfect trust is still difficult to achieve at the current stage. However, a really widespread adoption of Walmart's blockchain solution would not occur until all ecosystem players had a compelling reason to participate. Walmart should therefore perform more extensive trials in the food supply chain to ascertain the blockchain's true contribution, as well as educate stakeholders about the technology and explain the advantages they can get from using it.[22]

8 Current issues and upcoming research directions

Blockchain is a new technology that has only recently started to be used in a variety of businesses. The question of whether BCT is the best solution to solve the application challenge arises naturally when considering the application of BCT to new sectors. Emerging BCT is still in its early phases of development, making it difficult to find viable applications at an early stage. In order to realize this vision in practice, numerous significant difficulties and problems must be overcome. Future research will focus on the difficulty of using BCT to control food safety (Fig. 5).

8.1 Technical difficulties

As far as BCT is concerned, it must first show that it has the scalability, speed, and security requirements to support the suggested use cases. The speed of data transmission will be considerably increased with the development and use of 5G technology, and the drawbacks of BCT may be resolved. The current high development cost of blockchain systems is a significant obstacle. By excluding mediators, blockchains may result in large cost reductions, although in other cases, they might not have a competitive edge over already-existing solutions in developed markets. The blockchain must pay extra money to store data in an increasing ledger in addition to the expense of information validation. However, by carefully planning and implementing an application, these problems can be solved.

8.2 System functionality

There are still a few significant problems that need to be solved. This concept first calls for the creation of a database that can enable blockchains that evaluate each transaction's parameters and communicate with delayed and low-latency blockchain systems. Consumers may have significant opposition even if it is anticipated that these can be built (in fact, some programs have this goal), especially for privacy concerns. It is not yet obvious whether growers or farmers want to openly record their growing status in the blockchain, despite the fact that expenses could be decreased. Therefore, when implementing blockchains in the control system of food safety, how information is recorded in the ledger, such as safeguarding the privacy and anonymity of persons and farmers, growers, and exclusive patented production techniques and processes, may prove to be a critical concern.[14]

8.3 Blockchain infrastructure

The majority of people do not now comprehend BCT, and it will take some time before it is fully accepted. The infrastructure

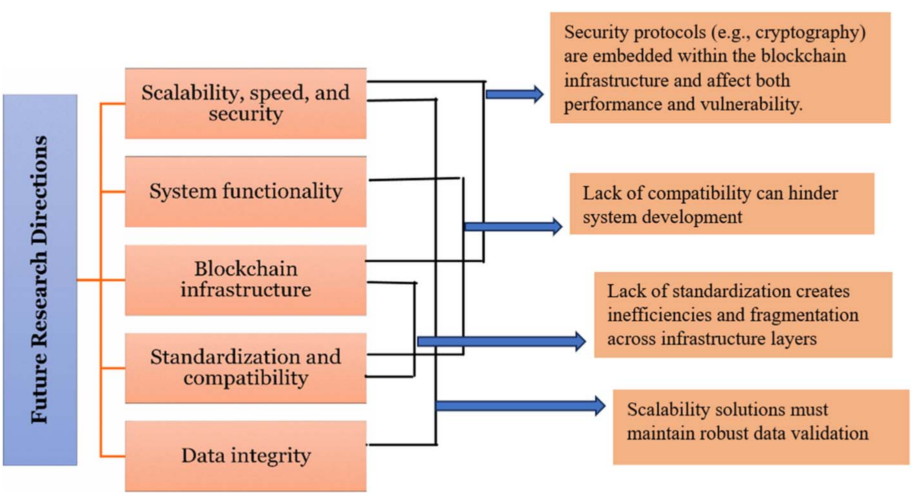

Fig. 5 Future research focus: addressing key limitations in blockchain implementation.

needed to fulfil all the demands of the blockchain-based food supply chain system is lacking. Therefore, developing the blockchain system will take a lengthy period.

8.4 Standardization and compatibility

It is crucial that blockchain solutions be compatible and standardized across businesses. To promote interoperability protection between technical solutions for collaborative trust and information, blockchain architectural standards must be defined. Another challenge is ensuring that various blockchain systems are compatible and uniform.

8.5 Data integrity

BCT can guarantee the veracity of the data that have been captured. However, as human mistake might compromise the accuracy of the input data, it may take some time from data generation to blockchain input. Assuring the accuracy of the information in this procedure is therefore a significant task. BCT also updates big data in real time with the help of integrated decentralized networks with already collected data. IoT sensors, smart contracts or enterprise systems transfer automated data such as temperature data recorded during food supply or a smart contract that releases payment as the package is delivered.[61]

9 Sustainability

9.1 Resilience and resource efficiency

Along the entire food value chain, information about environmental factors can be collected using BCT to identify risks and pressures. In order to assist stop outbreaks of foodborne illness and recalls, BCT may save and communicate data, such as that on humidity and temperature during transportation and storage. Individualized perishability dates on food goods offered by BCT can reduce food waste in households. These dates are tailored to the circumstances in which the food was manufactured, transported, and kept. Reduced environmental impacts on food systems can be achieved by more effective resource planning and transportation, made possible by more visibility and transparency.

9.2 Sustainable and healthy diets

BCT enables the consumer to make educated decisions and is in line with consumer aspirations for products that are healthy, morally upright, and environmentally friendly. As a result, customers can make thoughtful judgments that are less influenced by the media. In order to safeguard food safety and prevent food fraud, BCT may also be utilized.

9.3 Circular economy

BCT encourages better planning and can enhance circular production flows. It has been demonstrated that consumers can be encouraged to recycle food containers in response to the rise in food packaging if given the chance to earn cryptocurrency. BCT can be used to monitor and address problems like resource waste and biodiversity loss.

9.4 Profitability and efficiency

BCT is a part of a larger shift toward agriculture and food production that is more data-driven. Big data, the Internet of Things (IoT), artificial intelligence (AI), and machine learning, combined with physical developments (such as sensors, machines), are acknowledged to be revolutionary for food systems, aiding actors along the food chain in making decisions. As direct effects of disintermediation, cost reduction and efficiency improvement can increase economic sustainability while lowering market uncertainty and inefficiency. BCT eliminates the requirement for a third party to maintain the data centrally because it can capture several parameters of a food product. By automating data verification, smart contracts can simplify certification administration and aid in process optimization. These smart contracts execute actions without any need for manual input as soon as the conditions are met or as soon as the delivery of product is done. Several platforms like Ethereum, Cardano, and Hyperledger Fabric use smart contracts for automation, distribution, and transparency. Recently, Daraghmi and coworkers developed AgroChain, a blockchain-based system with smart contracts for role management, supply chain contracts, and smart contracts for execution and verification for use in agricultural supply chain.[62] This eliminates administrative costs, legal fees, and human intermediaries. These smart contracts ensure integrity, reduce overall cost, thereby increasing profitability, and strengthen consumer trust by ensuring transparency.

9.5 Sustainable supply chains and fair trade

The greatest benefit of BCT is its enhanced transparency, traceability, and trust. Let's say information on certain characteristics of a food product can be transparently communicated to the consumer. Then, by verifying the credentials, this can satisfy consumer demand for purchasing ethical and sustainable product and enable informed decision-making. It has been demonstrated that as supply chains become transparent, customers would be able to directly verify ethical working conditions as a component of social sustainability. As a potential result of BCT, shorter supply chains may potentially improve farmers' standing and promote community growth.

9.6 Transparency, traceability and trust

BCT is anticipated to increase sustainability, restore consumer trust, and identify and stop supply-chain participants' dishonest and fraudulent behavior. It lessens the knowledge imbalance that currently exists in centralized supply chains and encourages greater parity in the power of negotiation between partners. Regulators can readily and frequently monitor markets to stop collusion by increasing openness. Those businesses who embrace BCT will probably profit from quick responses to rising consumer and governmental demands for greater openness in the food supply chains. The type of data that must be made public, though, has not been standardized. Although it necessitates structural and organizational changes, governance is viewed as essential for successful and sustainable technology deployment.

10 Future research

As BCT spreads throughout the food chain, additional study is needed to address practical concerns regarding the design of BCT services, user experiences of software and apps, and other matter pertaining to the present documentation and certification processes. As the technology must perform in their daily operations, future study should incorporate qualitative evaluations of businesses along the chain, including upstream supply chain participants (such as farmers and smaller agri-food corporations). To further our understanding of the subject, quantitative research involving the food industry and other actors will also be required as BCT is utilized more frequently in the food chain. While taking into mind the function of policies, it can also be necessary to establish industry standards for data exchange and openness. Further research is needed in this area, but integrated systems employing AI, IoT, and BCT can increase resource efficiency and reduce the consumption of input supplies in food production. Last but not least, comparing the environmental sustainability of food in conventional systems and supply chains made possible by BCT could help with quantitative reasoning about the value BCT can offer to more environmentally friendly food systems.

11 Environmental benefits of blockchain technology in the food supply chain

BCT offers a range of environmental benefits, especially in the food supply chain, particularly by reducing waste, increasing traceability for producers or manufacturers, retailers as well as consumers, and transparency.[22] This traceability reduces unsustainable practices in the industry. For instance, a BCT-based model developed for the Taishan tea industry addressed data security issues while optimizing the problems of traditional traceability methods.[63] BCT also plays a crucial role in reducing the post-harvest losses of perishable goods by facilitating traceability through the supply chain and allowing faster interventions in preventing damage of goods.[22] Moreover, the automation of processes possible through BCT can ensure real-time tracking, reduce delays and contribute to efficient resource use which in turn reduces waste. According to a recent study, the Italian tomato market lacks a reliable tracking system which leads to an exploitative supply chain and unfair pricing control by the dealers. To overcome this, the researchers developed a blockchain-smart contract system model which ensured transparency and traceability in sustainable tomato supply chain management.[64] Overall, BCT provides a more environmentally responsible and efficient food supply system.

12 Conclusion

Improved visibility and traceability as well as immutability of records are recognized advantages of BCT. In today's extensive and intricate food supply chains, BCT can help to build trust, efficiency, and to some extent fairness. Increased transparency makes it possible for consumers to educate themselves, which can change demand in favor of more sustainable products, support farmers' rights, and spread ethical behavior. In general, spreading accurate and reliable information about food origin along with additional details like recipes or expiration dates can raise awareness and help the transition to a more sustainable food system. However, from an environmental standpoint, the benefit of BCT itself seems to be limited to resource savings brought on by recall prevention and improved supply-chain planning.

Data availability

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

Author contributions

Devraj V. Rajput: conceptualization, investigation, writing – original draft, writing – review & editing. Pavankumar R. More: writing – review & editing. Preeti A. Adhikari: writing – review & editing. Shalini S. Arya: conceptualization, writing – review & editing, visualization, supervision.

Conflicts of interest

The authors declare that they have no direct or indirect known competing financial interests or personal relationships that could have appeared to influence the subject matter discussed and reported in this paper.

References

1 W. Mougayar, *The Business Blockchain: Promise, Practice, and Application of the Next Internet Technology*, John Wiley Sons, 2016.
2 S. E. Chang, Y. C. Chen and M. F. Lu, Supply chain re-engineering using blockchain technology: A case of smart contract based tracking process, *Technol. Forecast. Soc. Change*, 2019, **144**, 1–11.
3 T. M. Choi, Creating all-win by blockchain technology in supply chains: Impacts of agents' risk attitudes towards cryptocurrency, *J. Oper. Res. Soc.*, 2021, **72**, 2580–2595.
4 T. M. Choi, X. Wen, X. Sun and S. H. Chung, The mean-variance approach for global supply chain risk analysis with air logistics in the blockchain technology era, *Transport. Res. E Logist. Transport. Rev.*, 2019, **127**, 178–191.
5 M. E. Peck, Blockchain world - Do you need a blockchain? This chart will tell you if the technology can solve your problem, *IEEE Spectrum*, 2017, **54**, 38–60.
6 P. Dutta, T. M. Choi, S. Somani and R. Butala, Blockchain technology in supply chain operations: Applications,

challenges and research opportunities, *Transport. Res. E Logist. Transport. Rev.*, 2020, **142**, 102067.
7 Y. J. Cai, T. M. Choi and J. Zhang, platform supported supply chain operations in the blockchain era: Supply contracting and moral hazards, *Decis. Sci.*, 2021, **52**, 866–892.
8 V. Babich and G. Hilary, Distributed ledgers and operations: What operations management researchers should know about blockchain technology, *Manuf. Serv. Oper. Manag.*, 2020, **22**, 223–240.
9 R. Goyat, G. Kumar, M. K. Rai and R. Saha, Implications of blockchain technology in supply chain management, *J. Syst. Manag. Sci.*, 2019, **9**, 92–103.
10 J. Wu and N. K. Tran, Application of blockchain technology in sustainable energy systems: An overview, *Sustain*, 2018, **10**, 3067.
11 M. O'Dair and Z. Beaven, The networked record industry: How blockchain technology could transform the record industry, *Strateg. Change*, 2017, **26**, 471–480.
12 S. Ølnes, J. Ubacht and M. Janssen, Blockchain in government: Benefits and implications of distributed ledger technology for information sharing, *Gov. Inf. Q.*, 2017, **34**, 355–364.
13 G. Li, L. Li, T. Choi and S. P. Sethi, Green supply chain management in Chinese firms: Innovative measures and the moderating role of quick response technology, *J. Oper. Manag.*, 2020, **66**, 958–988.
14 Y. Xu, X. Li, X. Zeng, J. Cao and W. Jiang, Application of blockchain technology in food safety control: Current trends and future prospects, *Crit. Rev. Food Sci. Nutr.*, 2022, **62**, 2800–2819.
15 Z. Dong, F. Luo and G. Liang, Blockchain: a secure, decentralized, trusted cyber infrastructure solution for future energy systems, *J. Mod. Power Syst. Clean Energy*, 2018, **6**, 958–967.
16 V. Gatteschi, F. Lamberti, C. Demartini, C. Pranteda and V. Santamaría, Blockchain and smart contracts for insurance: Is the technology mature enough?, *Future Internet*, 2018, **10**, 20.
17 A. Kamilaris, A. Fonts and F. X. Prenafeta-Boldú, The rise of blockchain technology in agriculture and food supply chains, *Trends Food Sci. Technol.*, 2019, **91**, 640–652.
18 M. Tripoli and J. Schmidhuber, Emerging opportunities for the application of blockchain in the agri-food industry agriculture, *Food Agric. Organ. United Nations*, 2018, **21**, 1–11.
19 M. Lierow, C. Herzog and P. Oest, *Blockchain: the Backbone of Digital Supply Chains*, Oliver Wyman, 2017.
20 P. Olsen and M. Borit, How to define traceability, *Trends Food Sci. Technol.*, 2013, **29**, 142–150.
21 S. Sarpong, Traceability and supply chain complexity: Confronting the issues and concerns, *Eur. Bus. Rev.*, 2014, **26**, 271–284.
22 B. Tan, J. Yan, S. Chen and X. Liu, The impact of blockchain on food supply chain: The case of walmart, *International Conf. Smart Blockchain*, 2018, pp. 167–177.
23 A. Bernard, F. Broeckaert, G. De Poorter, A. De Cock, C. Hermans, C. Saegerman and G. Houins, The Belgian PCB/dioxin incident: Analysis of the food chain contamination and health risk evaluation, *Environ. Res.*, 2002, **88**, 1–18.
24 J. Borrell Fontelles and A. Nicolai, Regulation (EC) No 1935/2004 of the European Parliament and of the Council of 27 October 2004 on materials and articles intended to come into contact with food and repealing Directives 80/590/EEC and 89/109/EEC, *Off. J. Eur. Union*, 2004, **47**, 4–17.
25 C. Wales, M. Harvey and A. Warde, Recuperating from BSE: The shifting UK institutional basis for trust in food, *Appetite*, 2006, **47**, 187–195.
26 C. Xiu and K. K. Klein, Melamine in milk products in China: Examining the factors that led to deliberate use of the contaminant, *Food Policy*, 2010, **35**, 463–470.
27 N. Chammem, M. Issaoui, A. I. D. de Almeida and A. M. Delgado, Food crises and food safety incidents in European Union, United States, and Maghreb area: Current risk communication strategies and new approaches, *J. AOAC Int.*, 2018, **101**, 923–938.
28 H. Liu, W. A. Kerr and J. E. Hobbs, A review of Chinese food safety strategies implemented after several food safety incidents involving export of Chinese aquatic products, *Br. Food J.*, 2012, **114**, 372–386.
29 M. A. Resende-Filho and T. M. Hurley, Information asymmetry and traceability incentives for food safety, *Int. J. Prod. Econ.*, 2012, **139**, 596–603.
30 M. M. Aung and Y. S. Chang, Traceability in a food supply chain: Safety and quality perspectives, *Food Control*, 2014, **39**, 172–184.
31 O. Bermeo-Almeida, M. Cardenas-Rodriguez, T. Samaniego-Cobo, E. Ferruzola-Gómez, R. Cabezas-Cabezas and W. Bazán-Vera, Blockchain in agriculture: A systematic literature review, in *Communications in Computer and Information Science*, 2018, vol. 883, pp. 44–56.
32 J. Zhang, S. Zhong, T. Wang, H. C. Chao and J. Wang, Blockchain-based Systems and Applications: A survey, *J. Internet Technol.*, 2020, **21**, 202001.
33 S. Mostafalou and M. Abdollahi, Pesticides and human chronic diseases: Evidences, mechanisms, and perspectives, *Toxicol. Appl. Pharmacol.*, 2013, **268**, 157–177.
34 H. J. P. Marvin, E. M. Janssen, Y. Bouzembrak, P. J. M. Hendriksen and M. Staats, Big data in food safety: An overview, *Crit. Rev. Food Sci. Nutr.*, 2017, **57**, 2286–2295.
35 C. N. Verdouw, A. J. M. Beulens and J. G. A. J. van der Vorst, Virtualisation of floricultural supply chains: A review from an internet of things perspective, *Comput. Electron. Agric.*, 2013, **99**, 160–175.
36 M. L. Tseng, M. K. Lim, W. P. Wong, Y. C. Chen and Y. Zhan, A framework for evaluating the performance of sustainable service supply chain management under uncertainty, *Int. J. Prod. Econ.*, 2018, **195**, 359–372.
37 K. Leng, Y. Bi, L. Jing, H. C. Fu and I. Van Nieuwenhuyse, Research on agricultural supply chain system with double chain architecture based on blockchain technology, *Future Gener. Comput. Syst.*, 2018, **86**, 641–649.
38 T. K. Mackey and G. Nayyar, A review of existing and emerging digital technologies to combat the global trade in fake medicines, *Expet Opin. Drug Saf.*, 2017, **16**, 587–602.

39 Y. Guo and C. Liang, Blockchain application and outlook in the banking industry, *Financ. Innovat.*, 2016, **2**, 24.
40 B. Nielsen, M. J. Colle and G. Ünlü, Meat safety and quality: a biological approach, *Int. J. Food Sci. Technol.*, 2021, **56**, 39–51.
41 R. Fernández-Cisnal, M. A. García-Sevillano, T. García-Barrera, J. L. Gómez-Ariza and N. Abril, Metabolomic alterations and oxidative stress are associated with environmental pollution in Procambarus clarkii, *Aquat. Toxicol.*, 2018, **205**, 76–88.
42 P. L. Garnero, M. V. Monferran, G. A. González, J. Griboff and B. M. de los Ángeles, Assessment of exposure to metals, As and Se in water and sediment of a freshwater reservoir and their bioaccumulation in fish species of different feeding and habitat preferences, *Ecotoxicol. Environ. Saf.*, 2018, **163**, 492–501.
43 H. Feng, X. Wang, Y. Duan, J. Zhang and X. Zhang, Applying blockchain technology to improve agri-food traceability: A review of development methods, benefits and challenges, *J. Cleaner Prod.*, 2020, **260**, 121031.
44 N. Wang, N. Zhang and M. Wang, Wireless sensors in agriculture and food industry - Recent development and future perspective, *Comput. Electron. Agric.*, 2006, **50**, 1–14.
45 A. Kowalska, J. M. Soon and L. Manning, A study on adulteration in cereals and bakery products from Poland including a review of definitions, *Food Control*, 2018, **92**, 348–356.
46 V. Wiedemair, M. De Biasio, R. Leitner, D. Balthasar and C. W. Huck, Application of design of experiment for detection of meat fraud with a portable near-infrared spectrometer, *Curr. Anal. Chem.*, 2018, **14**, 58–67.
47 I. Pádua, A. Moreira, P. Moreira, F. Melo de Vasconcelos and R. Barros, Impact of the regulation (EU) 1169/2011: Allergen-related recalls in the rapid alert system for food and feed (RASFF) portal, *Food Control*, 2019, **98**, 389–398.
48 L. Ruiz-Garcia, L. Lunadei, P. Barreiro and J. I. Robla, A review of wireless sensor technologies and applications in agriculture and food industry: State of the art and current trends, *Sensors*, 2009, **9**, 4728–4750.
49 M. Andoni, V. Robu, D. Flynn, S. Abram, D. Geach, D. Jenkins, P. McCallum and A. Peacock, Blockchain technology in the energy sector: A systematic review of challenges and opportunities, *Renewable Sustainable Energy Rev.*, 2019, **100**, 143–174.
50 L. Herrmann, C. Felbinger, I. Haase, B. Rudolph, B. Biermann and M. Fischer, Food fingerprinting: Characterization of the ecuadorean type CCN-51 of *Theobroma cacao* L. using microsatellite markers, *J. Agric. Food Chem.*, 2015, **63**, 4539–4544.
51 S. Schelm, I. Haase, C. Fischer and M. Fischer, Development of a multiplex real-time PCR for determination of apricot in marzipan using the plexor system, *J. Agric. Food Chem.*, 2017, **65**, 516–522.
52 J. Wang and M. Chen, The food supply chain safety supervision study on the basis of the analytical hierarchy process, *Food Res. Dev.*, 2016, **37**, 162–166.
53 A. Kalia and V. R. Parshad, Novel trends to revolutionize preservation and packaging of fruits/fruit products: Microbiological and nanotechnological perspectives, *Crit. Rev. Food Sci. Nutr.*, 2015, **55**, 159–182.
54 K. Ropkins and A. J. Beck, Using HACCP to control organic chemical hazards in food wholesale, distribution, storage and retail, *Trends Food Sci. Technol.*, 2003, **14**, 374–389.
55 R. Casado-Vara, J. Prieto, F. De La Prieta and J. M. Corchado, How blockchain improves the supply chain: Case study alimentary supply chain, *Procedia Comput. Sci.*, 2018, **134**, 393–398.
56 A. Alourani and S. Khan, Halal Food Traceability System using AI and Blockchain, *J. Posthumanism*, 2025, **5**, 549–566.
57 K. Behnke and M. F. W. H. A. Janssen, Boundary conditions for traceability in food supply chains using blockchain technology, *Int. J. Inf. Manag.*, 2020, **52**, 101969.
58 F. Dabbene, P. Gay and C. Tortia, Traceability issues in food supply chain management: A review, *Biosyst. Eng.*, 2014, **1**, 65–80.
59 X. Shi, S. Chan, Information systems and information technologies for supply chain management, *Global Logistics-New Directions in Supply Chain Management*, The Chartered Institute of Logistics and Transport, Kogan Page Limited, 5th edn, 2007, pp. 177–196.
60 M. S. Bhat and S. Dubey, An overview of the effects of blockchain technology in food chain supply: A case study on Walmart, *Online J. Distance Educ. Elearn.*, 2023, **11**, 1205–1209.
61 F. Muheidat, D. Patel, S. Tammisetty, L. A. A. Tawalbeh and M. Tawalbeh, Emerging concepts using blockchain and big data, *Procedia Comput. Sci.*, 2022, **198**, 15–22.
62 E. Daraghmi, S. Jayousi, Y. Daraghmi, R. Daraghmi and H. Fouchal, Smart Contracts for Managing the Agricultural Supply Chain: A Practical Case Study, *IEEE Access*, 2024, **12**, 125462–125479.
63 K. Liu, P. Liu and S. Gao, Research on the Trusted Traceability Model of Taishan Tea Products Based on Blockchain, *Appl. Sci.*, 2024, **14**, 10630.
64 S. Safeer and C. Pulvento, Blockchain-backed sustainable management of italian tomato processing industry, *Agriculture*, 2024, **14**, 1120.

