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REVIEW

Blockchain Technology and Advancements in the Agri-food Industry

Thirukumaran R[1] · Vijay Kumar Anu Priya[1] · Vijayakumar Raja[1,2] · Shubham Nimbkar[1] · J. A. Moses[1] · C. Anandharamakrishnan[1,2]

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Abstract

Purpose The purpose of this article is to present the fundamental concepts, features, advantages, limitations, and possible applications in the agri-food supply chain. Blockchain technology helps in minimizing transaction costs and time, boosting process efficiency, and safety, including transparency, and increasing stakeholder confidence.

Methods Several scientific databases were searched with specific keywords and relevant research and review articles were collected and reported.

Results Maintaining data immutably and facilitating speedy monitoring through all phases of the food supply chain, blockchain increases transparency across all levels of the agri-food sector. Though the potential of the technology is proven, the implementation faces some challenges that require to be explored further with various conceptual frameworks developed for that purpose.

Conclusion This review explores the potential, features, and applications of blockchain technology to enable the flexible agri-food supply chain, various conceptual frameworks developed to achieve a traceable food supply chain, and barriers associated with the implementation of the technology.

Keywords Blockchain · Traceability · Transparency · Food supply chain · Smart contract · Digitalization

Introduction

Blockchain technology is a recently developed digital approach under Industry 4.0 that ensures data coherence and prevents data tampering. It was first introduced in the finance and e-commerce sectors primarily for exchanging values (Abeyratne & Monfared, 2016; The Economist, 2015). The term blockchain was first coined by Satoshi Nakamoto in the year 2008 when he created the first cryptocurrency, named Bitcoin, which enables transaction flexibility without intermediaries (banks) making them more transparent and less corruptible (Nakamoto, 2008; The Economist, 2015). Blockchain, primarily, is a distributed database in which transactional data or further digital occurrences can be recorded and shared among the supply chain members (Crosby et al., 2016). It relies on four principal components, namely decentralization, consensus, immutability, and democracy which make the system attractive and trustworthy (Yiannas, 2018). It authorizes the supply chain members to set up a decentralized agreement in an aligned occurrence and the present position of the transactions. Also, once a transaction is agreed upon and recorded in a block, it cannot be altered or changed. Furthermore, it utilizes a variety of technologies that are used in computer languages, i.e., public/private key cryptography, cryptographic hash function, and database technologies (Ge et al., 2017).

Agri-food sector is a diverse and complex sector offering an extensive range of operational and process difficulties. The sector must provide creative and sustainable options in order to increase agricultural output and product quality as well as meet the market need of a population that is constantly expanding (Konfo et al., 2023). Furthermore,

✉ C. Anandharamakrishnan
anandh@niist.res.in

J. A. Moses
moses.ja@iifpt.edu.in

1 Computational Modeling and Nanoscale Processing Unit, National Institute of Food Technology, Entrepreneurship and Management – Thanjavur, Ministry of Food Processing Industries, Government of India, Thanjavur, Tamil Nadu 613005, India

2 CSIR - National Institute for Interdisciplinary Science and Technology (NIIST), Ministry of Science and Technology - Government of India, Industrial Estate PO, Thiruvananthapuram, Kerala 695019, India

according to World Health Organization, thousands of people suffer annually because of contaminated food, also explaining that maintaining food quality and safety constantly creates a new challenge in the agri-food sector (Patel et al., 2023). Moreover, foodborne illness has caused a progressive decline in consumer faith in agri-food sector, which has an effect on the reputation of several companies. In order to assure the products safety and quality, consumers are currently requesting additional information on food items. Numerous studies have reported that consumers consider to know the origin of food which is the most significant piece of information. This suggests that agri-food industry should prioritize transparency in order to satisfy customer demand (Compagnucci et al., 2022). Food that are contaminated, adulterated, mislabelled, or misbranded might cause enormous social and economic losses for the world economy; these kinds of food frauds are bought up as nuisances since the perpetrators of these crimes typically possess a high degree of sophistication and technical understanding, making it difficult to hold them accountable. To overcome the current challenges, agri-food sector should undergo digital revolution. At the initial stage, traceability is the main component to be achieved in the agri-food and value-added product supply chain (Costa et al., 2013). The agri-food supply chain is responsible for the circulation of products from producer to end consumer. It is a complex system involving numerous stakeholders such as farmers, processors, wholesalers, retailers, and consumers. The primary function of a supply chain is to ensure the delivery of safe and authentic food products to the end consumer (Saberi et al., 2019). In this context, the safety and authenticity of food and agricultural products are of extreme importance. To ensure food safety, raw material quality, and inventory control stocks, traceability plays a major role and serves as a strategic tool (Aung & Chang, 2014; Dasaklis et al., 2019a, b).

Considering the several limitations of the existing agri-food supply chain adoption of blockchain technology can provide novel solutions for ensuring food safety, security, transparency, and traceability (Zhao et al., 2019). In food safety, blockchain plays a crucial role in avoiding the mismatching of information in the upstream and downstream processes; also, due to difficulties in real-time data collection information, food data is difficult to detect and communicate, making it extremely prone to unwanted manipulation or destruction. Although outer label of the food contains minimal data regarding the process, logistics, and distribution of the food, this is not sufficient as consumers may receive inaccurate data, suppliers in the traceability chain may become untrustworthy, and the ecological equilibrium may even be disrupted (Hong et al., 2021). So, implementing block chain guarantees the food safety, and increases the standards for government regulation to strengthen the trust between the industry, end user, and government. This increases the effectiveness and standard of food safety management (Lei et al., 2022). The present work describes the basic concepts, features, and potential of blockchain technology in the agri-food sector. Furthermore, special focus is given to the application of blockchain in the agri-food supply chain and the barriers associated with its application.

Fundamentals of Blockchain Technology

Blockchain is a decentralized database or a private ledger of every digital proceeding that can be performed and then shared between blockchain participants and verified at any point in the future (Crosby et al., 2016). It was created as a feasible approach for maintaining a contract in an untrustworthy decentralized distributed system (Nakamoto, 2008). This technology has been applied in supply chain domains to make the network more transparent, accurate, and reliable (Laaper et al., 2017). Blockchain, as the name suggests, is a series or list of blocks that contain certain information and it is secured by encryption algorithms (Al-Jaroodi & Mohamed, 2019). Each block holds information about a transaction. Figure 1 describes the formation and working of a blockchain.

Blockchain is divided into three types: consortium, private, and public. A public blockchain is a permissionless ledger in which anybody may check the transactions and perhaps also participate in the way of reaching a consensus. This feature makes blockchain the most transparent, trustable, and secure. On the other hand, a private blockchain is a small restricted network that has strict authorization control in data entry and does not allow all participants to take part in it. The presence of limited participants offers speed and scalability to the private blockchain. A consortium blockchain is somewhat decentralized version with a group of people in an organization present on a decentralized network. In this blockchain type, specific nodes have control of the consensus mechanism. Among the division consortium blockchain integrate effectively with the characteristics of blockchain (Eluubek kyzy et al., 2021). Moreover, the consortium is a hybrid form offering benefits of both public and private blockchain such as higher transaction speed and security. Also, the primary assumption is that consortium does not rely in one another and most likely in a central third party. So consortium blockchain has a huge potential and it is most suitable for application in agri-food sector.

Aside from the fact that it is a distributed shared ledger, blockchain is defined by three essential concepts: cryptography, smart contracts, and consensus. These ideas are aimed at demonstrating how implementing blockchain into the supply chain could result in a more trustworthy and sustainable ecosystem chain. Within the producing supply chain,

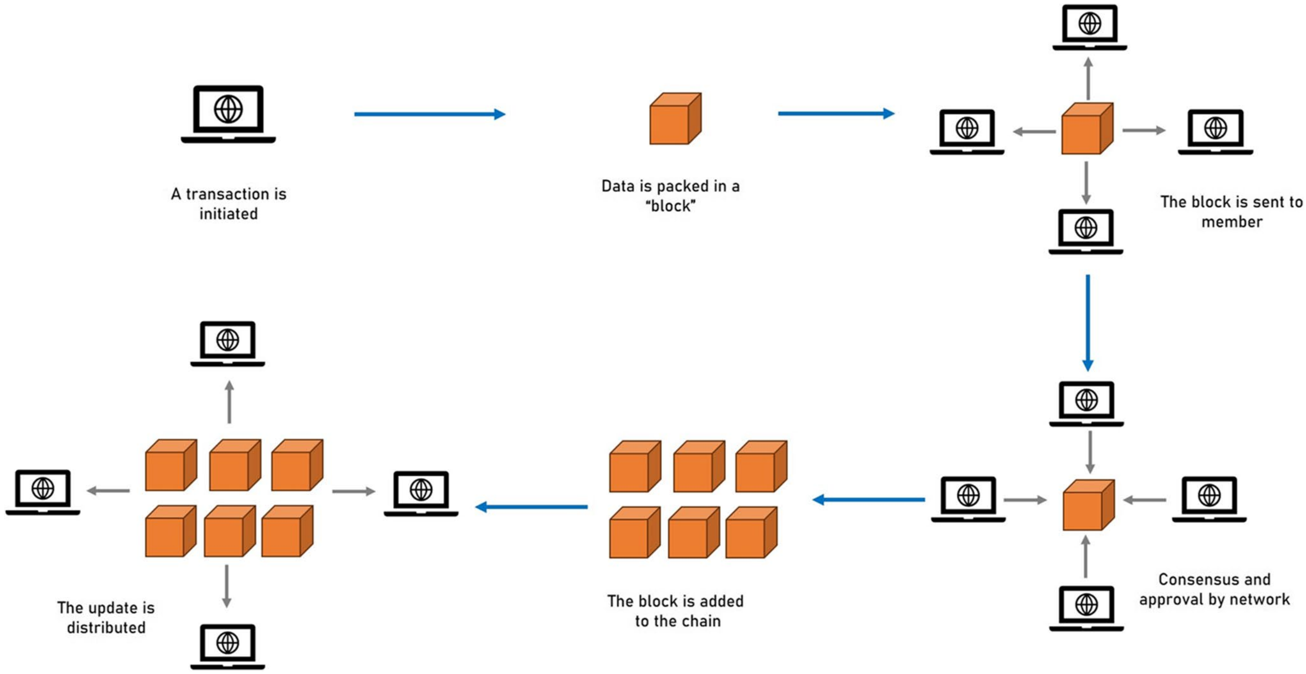

Fig. 1 Process flow of a typical blockchain system

transparency and traceability must be enhanced (Abeyratne & Monfared, 2016; Caro et al., 2018).

The Rising Need for Blockchain Technology

The growing awareness among consumers has broadened their focus towards safe, quality, authentic, and wholesome food rather than just quantity. In the context of food safety, WHO reports that every year nearly 600 million people are affected by eating contaminated food and about 4,20,000 people die worldwide (Casino et al., 2020). To avoid this, continuous monitoring of food quality throughout the supply chain is essential. Internet of things (IoT) applications will provide the present condition of the food, furthermore about the contamination information throughout the supply chain (Casino et al., 2020; Zhu et al., 2018). Another important aspect of food and agricultural products is authenticity. The true value of the item will not be known to the supply chain organizations and customers for validation and verification when there is a lack of transparency. This leads to several unscrupulous practices that involve the substitution of high-value products with low-cost substandard products. In some cases, this may pose a serious threat to consumer health. Some of the examples include the horsemeat scandal, toxic milk powder, salmonella outburst in Maradol papaya, and *E. coli* outburst in Chipotle Mexican Grill outlets (Saberi et al., 2019; Zhao et al., 2019). Such incidences reduce consumers' confidence in the products and can cause serious damage to the brand value of the company.

The conventional traceability systems are centralized, monopolistic, and opaque and certainly are not sufficient to gain consumer trust. Blockchain technology could be an excellent solution to overcome these limitations. It secures the data that is exchanged and creates a permanent, shareable, and actionable record (Patel et al., 2017). This ensures transparency and traceability which builds a better relationship between customers and shareholders in the food supply chain. Blockchain mainly reduces the risk, of food fraud, cost, and product loss. Blockchain technology is now transforming the world's food system by providing food safely to consumers (Wang et al., 2019). Over the past years, almost all the countries started their research towards the application of novel technologies in the agro-food sector to enable transparency and avoid food fraud.

To understand the research trends in blockchain technology, the SCOPUS database was searched with the keywords "Blockchain AND agri AND food." Italy, India, China, the UK, and Spain are the major players who focused their research on the utilization of blockchain technology in the agro-food industry. Figure 2A represents all major players and their scientific studies towards blockchain technology. Figure 2B represents the number of published articles in the past years.

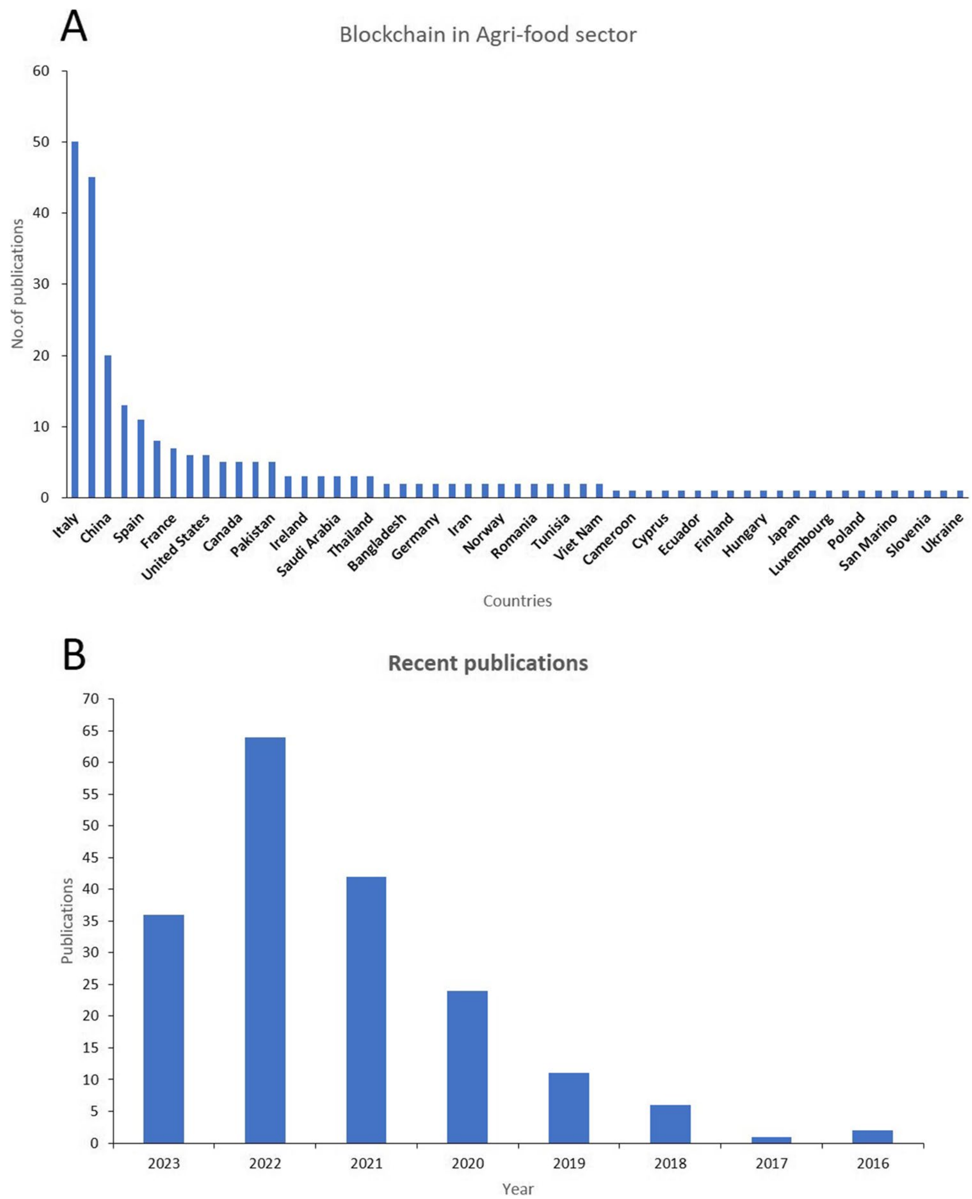

Fig. 2 Publication trends in blockchain technology in the agri-food sector. **A** Country-wise. **B** Year-wise. Source: Online SCOPUS database (www.scopus.com)

Features and Capabilities of Blockchain Technology

Decentralization

Decentralization refers to the elimination of a central authority that approves the transactions and promotes direct transactions among the users. Decentralized public blockchain assists in making decision-making transactions highly economical (Prashar et al., 2020). This removes the information inequality and provides equal power to all registered users in the network (Duan et al., 2020). In a conventional food supply chain, the flow of information is regulated by a central authority, i.e., a food manufacturer in most cases. In this system, despite stringent laws and regulations, there is scope for tampering with the information. In blockchain technology, the information records are not just made available to the stakeholders but it needs to be verified by them based on a consensus mechanism before being a permanent record. The stakeholders can save a copy of this permanently which can be accessed at any time in the future. This development can significantly increase transparency and build trust in the food supply chain (Yiannas, 2018).

Immutability

Immutability refers to the nature of the blockchain to remain unchanged and unaltered. Any new information is added in form of a block that is verified by the stakeholders and then becomes a permanent part of chain. Each added block is sequentially linked with the previous block. The block carries a timestamp and a hash value. Any tampering with the block alters the timestamp and associated hash value ultimately rendering the chain invalid. This prevents the modification, insertion, or deletion of any block inside the chain. If any error in the data block needs rectification, a new block is added and both blocks remain as a part of the record. Additionally, the blockchain also uses asymmetric cryptographic hash algorithm which adds to the security of blockchain. Contradictory to the conventional approaches, the data in blockchain is approved and stored over a network of peers, and therefore requires significant computational power to hack such large networks (Tharatipyakul & Pongnumkul, 2021). Data associated with the authenticity of foods, particularly high-value animal products, ingredients, and the presence of allergens is of significance for consumers. Furthermore, the transportation and storage conditions, especially in the case of perishables, determine the shelf life and safety of such foods. The immutability of such data through blockchain ensures that the data cannot be falsified and can act as evidence for different claims such as organic, halal, and fair trade food (Kamble et al., 2020; Queiroz et al., 2019).

Transparency

In a conventional food supply chain, the information is controlled in a centralized manner. Although some popular food brands have opened up information to consumers, this information is not sufficient to gain consumer trust and confidence (Yu & Nagurney, 2013). Furthermore, in the case of certifications such as halal and organic, consumers are willing to pay the price but in return, quality assurance and confidence are expected which a conventional approach provides to fail. In blockchain technology, the added information cannot be altered and is available to all peers including the consumers. This will be useful for increasing transparency and trust among different stakeholders and importantly consumers.

Smart Contract

Smart contracts are the contracts present in the digital form on a blockchain that run once some predetermined conditions are met. The conditions of the contract are written in the code of the blockchain, which once met, a network of computers executes the contract immediately. These actions could be notification, fund transfer, registration, sharing or transfer of keys, etc. One such example of a smart contract in the food supply chain is explained by Kamilaris et al. (2019) where the buyer gets automatic access to the warehouse once the payment is verified. The main advantages of the smart contract include high availability, low transaction cost, non-repudiation, and pseudo-anonymity (Dos Santos et al., 2021). Additionally, it is rapid, requires less paperwork, and builds trust among peers (Duan et al., 2020).

Sustainability

Social, economic, and environmental issues all have a role in the food supply chain's long-term viability (Wognum et al., 2011). Food waste is a big issue that has an impact on the supply chain (Shafiee-Jood & Cai, 2016). During outbreaks of food-borne disease, there are several challenges and problems in relation to the food supply chain's sustainability. Highly transparent food supply chains are required so that the specific cause and origin of a food-borne disease outbreak may be determined, resulting in the disposal of just the contaminated goods. Furthermore, because technology-enabled transparency allows for accurate and speedy approaches to controlling foodborne disease outbreaks, one should expect a huge depletion in healthcare expenses and development in public food-industry surveillance.

Applications of Blockchain in the Agri-food Sector

Blockchain implementation in the supply chain systems improves the transparency of the entire system avoiding the untrusted sectors in the system. This helped in the technology's rapid growth in cryptocurrency and other emerging sectors (Manski, 2017; Sharma, 2017). Agri and food supply chains have undergone rapid growth with new technologies being implemented for sustainable practices (Dujak & Sajter, 2019; Tripoli & Schmidhuber, 2018). Most of the agricultural products are put into some multi-stage supply chain in which customers act as the end node of the chain (Maslova, 2017). The agriculture and food supply chain in India is demand driven and undergo considerable levels of production loss which requires a systematic and strategic planning for its minimization (Patidar et al., 2018). The focus of blockchain technology works on the collection of data and processing of it in a trusted and organized network in order to aid transparency over the supply chain, as conventional food supply chain undergoes data fragmentation. Thus, the application of blockchain technology in various fields ensures a specially designed, organized, and trusted supply chain in the food sector.

This section discusses the various applications of blockchain technology in agriculture and the food supply chain. Though blockchain integrated the sectors in the food supply chain, we discuss the major focus of the technology in individual sectors.

Agri Supply Chain

Though the application of blockchain in agriculture is still in its introductory phase, its establishment in agricultural production and transportation could efficiently improve crop production and safety during transportation through the approach of smart agriculture. A framework for the digitalization of food production using blockchain technology is proposed in a recent work, which is called Food-SQRBlock. This proposes a blockchain-based framework to digitalize food production data through four phases, such as production, processing, transportation/distribution, and retailing (Dey et al., 2021). In addition, ICT-based tools and technologies such as Internet of Things (IoT), sensors, and machine learning were studied for their applicability and scalability in block chain based smart agriculture by recent researchers.

Farmers' cooperatives are a tool for developing nations to improve their competitiveness (Chinaka, 2016). Every farmer can gain a huge part of the crop's cost that they grow by joining cooperatives (FarmShare, 2017). FarmShare is a hybrid food value chain that seeks to establish land proprietorship, community collaboration, and self-supporting local financial prudence. It is an extension of the community-supported agricultural system, utilizing the blockchain to improve community engagement while reducing administrative expenses, decentralized consensus, token-based preferred stock, and digital governance are being used (FarmShare, 2017). AgriLedger is another block chain based smart solution system which utilizes a distributed crypto ledger to build confidence between smaller African cooperatives (AgriLedger, 2017). The researcher (Davcev et al., 2018) presented novel strategies that result in recognized cooperative applications and services between farmers as well as other chain entities inside the agro-food network. OlivaCoin is a Business-2-Business (B2B) platform for olive oil commerce that supports the olive oil business by reducing total financial costs, increasing transparency, and making global markets more accessible (IBM, 2016). Furthermore, several entrepreneurs, such as Arc-Net, Bart, Digital, Provenance, and Bext360, help small farmers by providing technologies that improve product traceability. Recently, the Soil Association Certification teamed up with Provenance to test technologies that monitor organic food's journey (Soil Association Certification, 2018). By utilizing blockchain, farmers (i.e., cooperative members) might benefit from insurance policies that protect them from unexpected weather conditions which impact their crops, as well as other hazards such as natural calamities (Jha et al., 2018). Block chain can also effectively be used to regularize the process of supporting farmers droughts, floods, and other severe weather events that overwhelmed their crops under the ARBOL initiative, which is based on personalized agreements (ArbolMarket, 2019).

Smart greenhouse models enabled with IoT-based remote monitoring and automation are becoming popular in agriculture. However, due to their large-scale disseminating nature, these models lack privacy and security. Integration of blockchain with a smart greenhouse is reported to enhance the security/privacy and prevent single point failure to improve overall efficiency (Patil et al., 2017). In another work, a smart greenhouse with IoT and deep learning is integrated with blockchain technology. This technology successfully allowed the integration of various data (sensor-collected and manually entered) from multiple sources which can be shared among its stakeholders. This approach allows to recollect all data related to the crops by calling out different stakeholders of the blockchain. Additionally, it enables saving and maintaining the data in irreversible way, remotely executing decisions which further results in improved productivity and reduce the cost (Frikha et al., 2023). Digital democratization of agriculture using blockchain-based electronic agriculture also enhances the efficiency of production, boosts the income, reorganizes incentives, and addresses the needs of the agricultural community (Chen et al., 2020).

Food Processing

Traditional food production systems are generally centralized and have trust related concerns, as it has the possibility of falsifying information. Food safety is primarily associated with the raw material quality, processing conditions, and maintenance of hygiene. In case of food processing operations dealing with large sample volumes, a small error in any of the processing unit operation or data communication can lead to the failure of whole batch. Blockchain technology is useful in the intelligent and in-process collection of data related to the such quality and safety of foods within food processing line and share it among the stakeholders (Yiannas, 2018). Once this data becomes a part of the blockchain record, it cannot be altered which ensures the food safety and builds the confidence among the consumers. Additionally, it strengthens the food traceability and smoothen the food recall in case of any food safety incident. Blockchain systems also have the flexibility of associating the authorities (including government agencies) involved in ensuring food safety and keep effective control over food quality (Xu et al., 2022).

Blockchain integrated with IoT systems is proved to be the efficient approach for the real-time monitoring of quality-related information using sensors, based on which it creates secure blocks and transactions (Casino et al., 2020; Rejeb, 2018). Thus, adjusting the frequency of transactions and identifying the heavy processes will help control the transaction fees (Longo et al., 2020).

Adamashvili et al. (2021) have proposed a model for the application of blockchain in the wine supply chain. In this study, the blockchain implementation strategy was presented focusing on predicting the quality of wine based on the variety, maturity, origin, treatments undergone, crushing quality and method, utensils used, method of packaging, storage condition, temperature, transportation, and so on (Novikova & Naumova, 2020). Members/participants of the blockchain have a set of rules that will be followed during the validation of the nodes and transactions, which brings trust towards the system and the members. The conceptualization of the blockchain framework for the wine supply chain starts from the vineyards. The main component of a good wine is its main ingredient, which is grapes in this case. Initially, the climate and geographical conditions will be fed into the blockchain system. Producers are key players in the harvest and delivery of the product. During the harvest, producers will check for the quality of the grape and will represent the quality of grapes with different indications. The wine manufacturer will collect the data on the variety/quality (from farmer), supplier information, processing conditions, and physicochemical quality. From the manufacturer, the product moves to the wholesaler who is responsible to collect the final product and supplies to the retail stores and collects the data of the same, and uploads to the system. The details collected are linked into the distributed ledger so the end-users can get access to all the information. Proper validation of information by all the actors in the supply chain is neceaasary to track back the history in case of an outbreak. The proposed blockchain framework for the wine supply chain The author has also developed a simulation roadmap for this technology, which can be used for the selective recall of low-quality products from the market.

Food Supply Chain Management

Blockchain technology might be used as a credit evaluation tool to improve the efficiency of food supply chain monitoring and management. It might even be used to increase the surveillance of international agricultural agreements, such as those negotiated by the World Trade Organization and the Paris Climate Change Agreement (Tripoli & Schmidhuber, 2018). For example, AgriBlockIoT (Caro et al., 2018) is a completely decentralized, blockchain-based solution for agri-food supply chain management that can seamlessly connect IoT devices that generate digital data throughout the chain. Davcev et al., (2018) conducted a similar research by integrating IoT sensors and cloud technology which were put forward for the administration of a grape estate close to Skopje, North Macedonia. Pinna and Ibba (2018) found that blockchain-based contracts can help to prevent labor exploitation in agriculture by safeguarding employees with temporary agreements and employment agreements. It will be trouble-free for authorities to ensure honesty in settlement and tax collection when labor agreements are included in the blockchain. Coca-Cola has tried to identify forced labor in the sugarcane sector using blockchain (Gertrude Chavez-Dreyfuss, 2018).

Advanced deep learning (ADL)-based techniques assisted IoT-block chain platforms in the food supply chain to broaden the visibility with improved feasibilities of digitalization and provenance in the food sector. ADL-based predictions could help to make industrial policy decisions (Khan et al., 2020). Blockchain can also provide a feasible framework to monitor the industrial supply chain traceability in food industries. This would help protect processed foods from any vulnerable health hazards. The application of BT in a dairy supply chain is said to improve product counterfeiting and enhance trust in the industry (Shingh et al., 2020). An information management system for poultry based on BT has been developed which consists of the nodes at which the recordings of information in poultry rearing are done to identify the contaminated products (Ibrahim et al., 2021).

Food Quality Monitoring During Transportation and Storage

Food security is defined by the Food and Agriculture Organization (FAO) as a scenario in which "all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life." In emergencies such as violent political, natural disasters, and ethnic conflicts, achieving this goal has proven exceedingly difficult. Blockchain is viewed as a tool to make international aid more transparent, remove middlemen from the distribution process, make data and goods traceable and available, and potentially manage more quickly and effectively during humanitarian crises. To give an example, digital food vouchers were provided to refugees of Palestinian in Jordan's Azraq camp through an Ethereum-based blockchain (UNWFP, 2017), where the vouchers can be spent using biometric data (Blockchain for Zero Hunger, 2017; Built, to adapt, 2018).

Food quality control has been more complicated as foreign trade flows have increased (Creydt & Fischer, 2019). According to the Centers for Disease Control and Prevention (CDC), food adulteration makes 48 million Americans sick each year, with 3000 deaths (CDC, 2018), (Tripoli & Schmidhuber, 2018). Oceana conducted a study on sea-based food fraud in 2016, finding that one-third of seafood is (Sealed) and labeled improperly (Oceana, 2013). Walmart and Kroger became the first organizations to adopt blockchain and integrate it into their supply chains (CB Insights, 2017), focusing on case studies using Chinese pork and Mexican mangoes at first (Kamath, 2018). Initial findings from the studies indicated that traditional techniques took nearly 6.5 days to find out the source and journey of a box of mangoes from the shop to the farmland where they were cultivated, but blockchain provided the same data in just a very few seconds (Wass, 2017). It was recently proposed to integrate blockchain with the IoT for real-time tracking and tracing of physical information based on the HACCP (Tian, 2017). It is especially important for preserving the cold chain delivery of perishable food goods. In particular, ZetoChain uses IoT sensors to monitor the environment at every step in the cold chain (Zeto, 2018).

The application of blockchain technology in improving food supply chain traceability is presently evolving, as it is essential to adopt the technology in a supply chain involving several stakeholders. Though an integrated blockchain system in a food supply chain is not established commercially yet, there are several proposed prototypes to ensure better traceability which could represent the potentiality of implementing blockchain in food supply chain along with product identifiers. These types of prototypes help in capturing the data across FSC, segregating and processing it through a food quality index (FQI) algorithm to generate an FQI value that represents the quality of the food at any point in the supply chain (George et al., 2019). Applications of BT-based multimode sensors for quality monitoring in cold storage have been studied by Feng et al. (2020) which collect the microambient changes in the environment and thus predict the quality of stored shellfish with improved information transparency.

The role of blockchain implementation also has the potential to track and measure the carbon footprint of a food supply chain in food processing facilities with a significantly larger number of nodes (Shakhbulatov et al., 2019). Though the proposed approaches are studied for their feasibility for establishment in FSC, the future requirements need to be addressed while establishing it on a large-scale supply chain network.

Food Integrity

The safe interchange of food across the supply chain is referred to as food integrity. Every participant must disclose exact information about the origin of products. Food manufacturers might utilize the blockchain to tackle fraudulent activity by spotting and tracing outbreaks back to their source as quickly as possible (Levitt, 2016). According to a current estimate, the value of food traceability by 2019 would be $14 billion (MarketsandMarkets Research, 2016). Various organizations, including start-ups, are utilizing blockchain to improve the food supply chain's integrity. Cargill Inc., an agricultural corporation, seeks to use blockchain to allow customers to track their turkeys from the departmental store to the farm where they grown-up (BUNGE, 2017). In a recent blockchain trial, turkeys and animal welfare were taken into consideration (Hendrix Genetics, 2018). Carrefour, a European supermarket chain, is implementing blockchain to verify food regulations and track origins in a variety of categories, including meat, fruits, seafood, dairy, and vegetables (Carrefour, 2018). Downstream beer (Ireland Craft Beers, 2018) is the primary organization there in the beverage industry to employ blockchain technology, which reveals complete information about the beer, including its ingredients and brewing techniques. As an assurance of transparency and authenticity, each aspect of their crafted beer is documented and uploaded on the blockchain. Consumers scan the QR code across the front side of the bottle with their smartphones and be brought to an internet site in which they can learn about everything from the base ingredients to the bottling process. Some of the other industrial applications which are utilizing blockchain technology into their supply chain are listed in Table 1. A sustainable blockchain framework has been recently proposed by Ali et al. (2021) for the halal food supply chain to enhance integrity of SC. It comprises of several challenges that are vital to small- and medium-scale enterprises in halal food supply chain blockchain implementation.

Challenges and Research Directions

Integration with Existing Systems

Implementing block chain in various sectors of the agri-food supply chain enables improved transparency and real-time data-sharing capabilities. However, integrating this technology into the supply chain has several critical behavioral barriers in terms of performance, social influence, conditions, behavioral intention, expectation, and trust. Regulatory ambiguity, lack of consistent guidelines and processes, privacy concerns, financial constraints, and knowledge gaps are some of the challenges in the blockchain. The centralized oversight structures of current information-sharing platforms as well as supply chain management also need to be restructured to fully realize the potentially transformative effects of BT in the agri-food supply chains (Fortuna & Risso, 2019). To overcome the abovementioned barriers, industries can cope up with the following: creating internal budget and internal sponsorship, creating strategy for bottom up information, seeking help from external advisors (consulting services), restructuring and educating existing units of organizational policies, scheduling in-house training, resource relocation, and integrating with the existing systems by taking proper with external advisors.

Table 1 Selected recent applications of blockchain technology in the agri-food supply chain

Food category	Project/initiative	Key factor	Positive impact	Shortcoming	Reference
Coffee	The group collaborated with Farmer Connect to create a new portable software named "Thank My Farmer"	Formally designed to encourage customers to track down the origination of their coffee to gain a better knowledge of the beans' qualities and the region in which they are grown	Customers can track the origination of coffee beans to ensure quality, and supply chain partners can monitor the progress of various activities involved with the manufacturing and distribution of coffee The blockchain also enables farmers to obtain a fair price for their crops, as well as more efficiently and effectively channel the movement of money and information	Reduced or low margins for farmers	(How Is Blockchain Changing the Coffee Industry?, 2020)
Shrimp	The Sustainable Shrimp Partnership (SSP) has teamed up with IBM to ensure comprehensive traceability for SSP shrimp customers using IBM's Food Trust ecosystem	Shrimp aquaculture is a safe, long-term, and profitable business	100% traceable (provides vital and transparent data) Antibiotic-free (during the manufacturing procedure, no antibiotics are used) Neutral impact on water (best practices for assuring that the water used maintains the same quality as when it was first used) ASC certified (the most stringent certification for aquaculture)	Scalability is an issue	(Sustainable Shrimp Partnership, 2018)
Mango	IBM and Walmart teamed with each other to track mangoes from the moment they are plucked until they reach consumers' hands	A mango's life cycle: from tree to shelf How can traceability be done in minutes/seconds rather than weeks in the event of a food safety concern?	Rapid, economical, trustworthy, and low-risk approach Use analytics to detect food fraudulent activity, enhance the safety of food, and reduce wastage, resulting in a more realistic food framework Enhance shelf-life management and eliminate expired product waste	Standardization is yet to be worked out In many situations, you'll need to connect blockchain to your organization's information system as well as other technologies like RFID labeling	(Kamath, 2018)
Turkey	Cargill is utilizing blockchain, a cryptographically secured ledger maintained by a network of computers and inspired by the one at the heart of Bitcoin	In this domain, blockchain technology is utilized to monitor turkeys from farm to market and to assist end-users in acknowledging where their turkeys come through	More effectively and efficiently track the food Greater transparency and more constant food safety regulations, among other things	For Indian farmers, it is too costly to invest	(Mike Orcutt, 2017)

Table 1 (continued)

Food category	Project/initiative	Key factor	Positive impact	Shortcoming	Reference
Tuna	Provenance collaborated with Humanity United and the International Pole and Line Foundation (IPNLF) on an initiative to track yellow-tailed tuna around Indonesia	The purpose of the mission was to employ a smartphone app in combination with blockchain and smart tagging to track the origins and credibility of socially sustainable certifications The aim is to create a thorough verification of consistency using a system that could be used across the supply chain	Interoperability to monitor and track product certification in a secured, continuous, and transparent system, as well as the entire system in which the data is implemented A unique ID will be produced when the fish is caught, and the unique ID will be physically connected to the fish by making use of Quick response codes and RFID tags	One of the challenges was integrating the system with current large-scale enterprise resource planning (ERP) systems, as most of them seem to not keep track of the goods as they move through the supply chain	(Provenance, 2016)
Olive	The Provence region of France, which produces excellent oil, has pioneered the Gestolive traceability management system	To help producers to show the good quality of their practices and products	Increase the income of the farmer Increase the transparency of the supply chain, in this way, it will enable consumers to trust the safety, quality, and origin of the products	If the oil leaves the industry, this system will not be able to track it	(IBM Food Trust Delivers Traceability, Quality Assurance to Major Olive Oil Brands with Blockchain, 2016; Alkhudary et al., 2022)
Beef	Beef Ledger is developing and commercializing a blockchain-enabled meat provenance stage and smart contracting payments system that smooths out payments and boosts client confidence in product authentication	In the Beef ledger Customers and other supply chain, participants will benefit from improved transparency and simplified transactions throughout the beef supply chain	Greater transparency Beef Ledger can monetize data value and guarantee that it is collected by people responsible for its production	While using the blockchain to cattle by itself may be feasible, it will not help farmers	(Beef Ledger, 2017)
Chicken	An ankle bracelet is used by the Gogo Chicken group to keep track of their hen. The movements and behavior of the hens are tracked via GPS tracking, which is subsequently made available on the internet	By establishing the origination of the food, the organization seeks to develop trust	Nearly one lakh birds have been equipped with GPS trackers so far	For Indian farmers, it is too costly to invest	(Adele Peter, 2017)
Milk	Nestlé joined together with OpenSc—the blockchain pilot program for food supply chain transparency	Blockchain technology allows customers to track their food back to its origin	Enhancing transparency and credibility	There is a lack of knowledge among policymakers and industrial experts	(Sanjeev Kumar Sharma, 2020)

Table 1 (continued)

Food category	Project/initiative	Key factor	Positive impact	Shortcoming	Reference
Palm oil	The Malaysian Palm Oil Council (MPOC) and BloomBloc teamed together to use blockchain to increase transparency and traceability in the palm oil industry	To track palm oil across its supply chain, it has created a blockchain-based mobile application and a web service Each tree, adds extra information from other checkpoints and is put into the system using a smartphone	Generates an end-to-end digital database that improves stakeholders' and end customers' transparency, reliability, and trust	The a need for the sector to utilize technology to reassure the public about the commodity's long-term sustainability	(Sanjeev Kumar Sharma, 2020)
Rice	The rice quality during shipping	Supervision and management	The rice value chain's activities were also recorded using blockchain, assuring the safety, and purity of rice along with the shipping activity	Accessibility is a significant issue, as is a lack of knowledge among authorities and technical experts	(Kumar & Iyengar, 2017)

Data Handling and Computational Resources

A barrier in implementing blockchain was anticipated to be the expense of computation and censoring the equipment necessary to run the entire network. The adoption of blockchain can necessitate extensive organizational and product modifications, which would cost a lot of money and effort (Tharatipyakul & Pongnumkul, 2021). The adoption of blockchain technology might be hampered by the expense of implementation. Investing vast amounts in computer technology may be the present problem for developing nations. Since the technology is at the birth phase, it is not fully developed and often requires trial period. To tackle the difficulties, industry can establish partnership and true relationship with the other companies, adopting part of the supply chain and consider scaling broader later based on the requirements; furthermore, partial supply chain scope simplifies initial adoption. Also, without any assistance from any third party, the blockchain handles all aspects of data storage and protection. Thus, the security of the data depends on the mechanism on blockchain technology. As the data is stored over a network, no specific data storage server is required (Li et al., 2019).

Unique Skill Set Requirements

Since the technology is new, there is a lack of technical expertise and a shortage of developers, so the technology hampered in its adoption (Motta et al., 2020). Many stakeholders lack knowledge of blockchain technology's benefits and have outdated perspectives. The education and expertise needed by many stakeholders to deploy a blockchain-based application may be lacking (Demestichas et al., 2020). The learning environments are still insufficient. For a small food firm, establishing and using such a system is not trivial.

Consumer Perception

Although emerging technologies increase transparency in food supply chains, several issues concerning technological acceptability by consumers and stakeholders remain unanswered. Lack of public awareness will lead to unfavorable perceptions of the technology. During outbreaks of foodborne disease, public perception and acceptability would be more crucial to consider than transparency-enabling technology. The benefits of transparency-enabling technology will be apparent to consumers, especially in the food supply chain, since they will have more access to information on food production (Astill et al., 2019). Another worry from the consumer's point of view is, if the consumer is prepared to spend more money for much more transparency in food items. Since blockchain is in the early stage, it will take a decade for the full-fledged implementation in the agri-food sector. Proper knowledge about the technology should be fed to the consumers.

Conclusion

In this manuscript, the implementation of the novel blockchain technology in the food industry and its uses in food supply chain management were presented. The rise of blockchain-based supply chain management is highlighted, which allows the development of shared, secure, decentralized ledgers, autonomous digital contracts (smart contracts), and trustworthy and protected networks. It also makes p-p transactions easier by lessening the involvement of brokers (intermediaries) in the system. As discussed, earlier blockchain technology will not only help to uplift the consumers, producers, and the supervision department, but it helps in uplifting the efficiency of the agri-food supply chain system by enabling its transparency. Certain standards will need to be met when technology penetrates food supply chains, resulting in more transparency. Even if IoT or blockchain-enabled systems are the most successful alternatives, food supply chains must employ cost-efficient techniques; elevated expenditures linked with this technology must be minimized, and enhanced transparency that results must contribute to revenue growth. Apart from the research requirements for commercializing a blockchain framework in an FSC, optimizing the granularity level of traceable units is also important which potentially describes the effectiveness of a blockchain architecture. When executed, technology-enabled transparency measures should minimize operational risk in the food supply chain while also ensuring data integrity, minimizing cybercrime, and safeguarding shareholder data. As this will speed up operations and cut processing times, transparent food production systems must allow for quick data exchange between stakeholders. This technology should also ensure that all parties involved comply with newly enacted rules and regulations. Furthermore, as indicated by the incorporation of new origins of data and technology as they become accessible, technology-enabled food manufacturing techniques should change over time. Even though transparent food production systems face several challenges and issues, the implementation of these technological advancements has the potential to make food production and supply chain transparent.

Declarations

Conflict of Interest The authors declare no competing interests.

References

Abeyratne, S. A., & Monfared, R. P. (2016). Blockchain ready manufacturing supply chain using distributed ledger. *International Journal of Research in Engineering and Technology, 5*(9), 1–10. https://doi.org/10.15623/ijret.2016.0509001

Adamashvili, N., State, R., Tricase, C., & Fiore, M. (2021). Blockchain-based wine supply chain for the industry advancement. *Sustainability (Switzerland), 13*(23), 1–19. https://doi.org/10.3390/su132313070

Adele Peter, F. (2017). *In China, you can track your chicken on–you guessed it–the blockchain*. https://www.fastcompany.com/40515999/in-china-you-can-track-your-chicken-on-you-guessed-it-the-blockchain. Accessed 5 Feb 2024

AgriLedger. (2017). http://www.agriledger.com/. Accessed 5 Feb 2024

Ali, M. H., Chung, L., Kumar, A., Zailani, S., & Tan, K. H. (2021). A sustainable blockchain framework for the halal food supply chain: Lessons from Malaysia. *Technological Forecasting and Social Change, 170*, 120870. https://doi.org/10.1016/J.TECHFORE.2021.120870

Al-Jaroodi, J., & Mohamed, N. (2019). Blockchain in industries: A survey. *IEEE Access, 7*(c), 36500–36515. https://doi.org/10.1109/ACCESS.2019.2903554

Alkhudary, R., Brusset, X., Naseraldin, H., & Féniès, P. (2022). Enhancing the competitive advantage via blockchain: An olive oil case study. *IFAC-PapersOnLine, 55*(2), 469–474. https://doi.org/10.1016/j.ifacol.2022.04.238

ArbolMarket. (2019). *ArbolMarket*. https://www.arbolmarket.com/. Accessed 5 Feb 2024

Astill, J., Dara, R. A., Campbell, M., Farber, M., Fraser, E. D. G., Sharif, S., & Yada, R. Y. (2019). Transparency in food supply chains : A review of enabling technology solutions. *Trends in Food Science & Technology, 91*(April), 240–247. https://doi.org/10.1016/j.tifs.2019.07.024

Aung, M. M., & Chang, Y. S. (2014). Traceability in a food supply chain: Safety and quality perspectives. *Food Control, 39*, 172–184. https://doi.org/10.1016/j.foodcont.2013.11.007

Beef Ledger, L. (2017). *Beef Ledger*. https://beefledger.io/. Accessed 5 Feb 2024

Building Blocks (2017). United Nations World Food Programme. https://innovation.wfp.org/project/building-blocks. Accessed 5 Feb 2024

Built, to adapt. (2018). *Can blockchain help feed the hungry?* https://builttoadapt.io/can-blockchain-help-feed-the-hungry-161b8fef7e24. *Accessed 5 Feb 2024*

BUNGE. (2017). Latest use for a bitcoin technology: Tracing turkey from farm to table. *The Wall Street Journal*. https://www.wsj.com/articles/latest-use-for-a-bitcoin-technology-tracing-turkeys-from-farm-to-table-1508923801. Accessed 5 Feb 2024

Caro, M. P., Ali, M. S., Vecchio, M., & Giaffreda, R. (2018). Blockchain-based traceability in agri-food supply chain management: A practical implementation. *IoT Vertical and Topical Summit on Agriculture-Tuscany (IOT Tuscany),* 1–4.

Carrefour. (2018). *The food blockchain*. https://www.carrefour.com/en/group/food-transition/food-blockchain. Accessed 5 Feb 2024

Casino, F., Kanakaris, V., Dasaklis, T. K., Moschuris, S., Stachtiaris, S., Pagoni, M., & Rachaniotis, N. P. (2020). Blockchain-based food supply chain traceability: A case study in the dairy sector. *International Journal of Production Research,* 1–13. https://doi.org/10.1080/00207543.2020.1789238

CB Insights. (2017). *How blockchain could transform food safety*. https://www.cbinsights. Accessed 5 Feb 2024

CDC. (2018). *Centers for disease control and prevention*. https://www.cdc.gov/foodborneburden/2011-foodborne-estimates.html. Accessed 5 Feb 2024

Chen, Y., Li, Y., & Li, C. (2020). Electronic agriculture, blockchain and digital agricultural democratization: Origin, theory and application. *Journal of Cleaner Production, 268*, 122071. https://doi.org/10.1016/J.JCLEPRO.2020.122071

Chinaka, M. (2016). *Blockchain technology--Applications in improving financial inclusion in developing economies: Case study for small scale agriculture in Africa*. Massachusetts Institute of Technology. http://hdl.handle.net/1721.1/104542. Accessed 5 Feb 2024

Compagnucci, L., Lepore, D., Spigarelli, F., Frontoni, E., Baldi, M., & Di Berardino, L. (2022). Uncovering the potential of blockchain in the agri-food supply chain: An interdisciplinary case study. *Journal of Engineering and Technology Management, 65*, 101700. https://doi.org/10.1016/j.jengtecman.2022.101700

Costa, C., Antonucci, F., Pallottino, F., Aguzzi, J., Sarriá, D., & Menesatti, P. (2013). A review on agri-food supply chain traceability by means of RFID technology. *Food and Bioprocess Technology, 6*, 353–366. https://doi.org/10.1007/s11947-012-0958-7

Creydt, M., & Fischer, M. (2019). Blockchain and more - Algorithm driven food traceability. *Food Control, 105*(March), 45–51. https://doi.org/10.1016/j.foodcont.2019.05.019

Crosby, M., Pattanayak, P., Verma, S., Kalyanaraman, V., et al. (2016). Blockchain technology: Beyond bitcoin. *Applied Innovation, 2*(6–10), 71.

Dasaklis, T. K., Casino, F., & Patsakis, C. (2019a). Defining granularity levels for supply chain traceability based on IoT and blockchain. *ACM International Conference Proceeding Series, Part, F1481*, 184–190. https://doi.org/10.1145/3312614.3312652

Dasaklis, T. K., Casino, F., Patsakis, C., & Douligeris, C. (2019b). A framework for supply chain traceability based on blockchain tokens. In *Lecture Notes in Business Information Processing: Vol. 362 LNBIP*. Springer International Publishing. https://doi.org/10.1007/978-3-030-37453-2_56

Davcev, D., Kocarev, L., Carbone, A., Stankovski, V., & Mitresk, K. (2018). Blockchain-based distributed cloud/fog platform for IoT supply chain management. *Eighth International Conference on Advances in Computing, Electronics and Electrical Technology (CEET)*, 51–58.

Demestichas, K., Peppes, N., Alexakis, T., & Adamopoulou, E. (2020). Blockchain in agriculture traceability systems: A review. *Applied Sciences, 10*(12), 4113. https://doi.org/10.3390/app10124113

Dey, S., Saha, S., Singh, A. K., & McDonald-Maier, K. (2021). FoodSQRBlock: Digitizing food production and the supply chain with blockchain and QR code in the cloud. *Sustainability, 13*(6), 3486. https://doi.org/10.3390/SU13063486

Dos Santos Abreu, A. W., Coutinho, E. F., & Bezerra, C. I. M. (2021). Performance evaluation of data transactions in blockchain. *IEEE Latin America Transactions, 20*(3), 409–416. https://doi.org/10.1109/TLA.2022.9667139

Duan, J., Zhang, C., Gong, Y., Brown, S., & Li, Z. (2020). A content-analysis based literature review in blockchain adoption within food supply chain. *International Journal of Environmental Research and Public Health*, *17*(5). https://doi.org/10.3390/ijerph17051784

Dujak, D., & Sajter, D. (2019). Blockchain applications in supply chain. In Arkadiusz Kawa & Anna Maryniak (Eds.), *SMART supply network* (pp. 21–46). Springer. https://doi.org/10.1007/978-3-319-91668-2_2

Eluubek kyzy, I., Song, H., Vajdi, A., Wang, Y., & Zhou, J. (2021). Blockchain for consortium: A practical paradigm in agricultural supply chain system. *Expert Systems with Applications, 184*, 115425. https://doi.org/10.1016/j.eswa.2021.115425

FarmShare. (2017). *Farmshare*. http://farmshare.org/. Accessed 5 Feb 2024

Feng, H., Wang, W., Chen, B., & Zhang, X. (2020). Evaluation on frozen shellfish quality by blockchain based multi-sensors monitoring and SVM algorithm during cold storage. *IEEE Access, 8*, 54361–54370. https://doi.org/10.1109/ACCESS.2020.2977723

Fortuna, F., & Risso, M. (2019). Blockchain technology in the food industry. *Symphonya. Emerging Issues in Management, 2*, 151. https://doi.org/10.4468/2019.2.13fortuna.risso

Frikha, T., Ktari, J., Zalila, B., Ghorbel, O., & Amor, N. B. (2023). Integrating blockchain and deep learning for intelligent greenhouse control and traceability. *Alexandria Engineering Journal, 79*, 259–273. https://doi.org/10.1016/J.AEJ.2023.08.027

Ge, L., Brewster, C., Spek, J., Smeenk, A., & Top, J. (2017). Blockchain for agriculture and food. In *Wageningen economic research*. www.wur.eu/economic-research. Accessed 5 Feb 2024

George, R. V., Harsh, H. O., Ray, P., & Babu, A. K. (2019). Food quality traceability prototype for restaurants using blockchain and food quality data index. *Journal of Cleaner Production, 240*, 118021. https://doi.org/10.1016/J.JCLEPRO.2019.118021

Gertrude Chavez-Dreyfuss, R. (2018). *Coca-Cola, U.S. State Dept to use blockchain*. https://www.reuters.com/article/us-blockchain-coca-cola-labor/coca-cola-u-s-state-dept-to-use-blockchain-to-combat-forced-labor-idUSKCN1GS2PY?mc_cid=d7c996d219&mc_eid=4c123074ea. Accessed 5 Feb 2024

Hendrix Genetics. (2018). *New blockchain project involving turkey and animal welfare*. https://www.hendrix-genetics.com/en/news/new-blockchain-project-involving-turkeys-and-animal-welfare/. Accessed 5 Feb 2024

Hong, W., Mao, J., Wu, L., & Pu, X. (2021). Public cognition of the application of blockchain in food safety management—Data from China's Zhihu platform. *Journal of Cleaner Production, 303*, 127044. https://doi.org/10.1016/j.jclepro.2021.127044

How is blockchain changing the coffee industry? (2020). https://123cryptocurrency.com/2020/02/how-is-blockchain-changing-the-coffee-industry/. Accessed 5 Feb 2024

IBM Food Trust delivers traceability, quality assurance to major olive oil brands with blockchain (2016). https://newsroom.ibm.com/2020-11-11-IBM-Food-Trust-Delivers-Traceability-Quality-Assurance-to-Major-Olive-Oil-Brands-with-Blockchain#:~:text=IBM. Accessed 5 Feb 2024

Ibrahim, A., Kamoliddin, U., Yoo, J. H., Lim, C. G., & Jeong, J.-C. (2021). Blockchain-based poultry information management system design and implementation using Hyperledger Fabric. *Journal of the Chosun Natural Science, 14*(3), 107–115. https://doi.org/10.13160/ricns.2021.14.3.107

Ireland Craft Beers. (2018). *Downstream beer*. https://www.downstream.io/. Accessed 5 Feb 2024

Jha, S., Andre, B., & Jha, O. (2018). *Smart contract weather risk protection for agriculture*. ARBOL. https://api.semanticscholar.org/CorpusID:212715468. Accessed 5 Feb 2024

Kamath, R. (2018). Food traceability on blockchain: Walmart's pork and mango pilots with IBM. *The Journal of the British Blockchain Association, 1*(1), 3712.

Kamble, S. S., Gunasekaran, A., & Sharma, R. (2020). Modeling the blockchain enabled traceability in agriculture supply chain. *International Journal of Information Management, 52*, 101967.

Kamilaris, A., Fonts, A., & Prenafeta-Boldύ, F. X. (2019). The rise of blockchain technology in agriculture and food supply chains. *Trends in Food Science and Technology, 91*(May 2018), 640–652. https://doi.org/10.1016/j.tifs.2019.07.034

Khan, P. W., Byun, Y. C., & Park, N. (2020). IoT-blockchain enabled optimized provenance system for food industry 4.0 using advanced deep learning. *Sensors, 20*(10), 2990. https://doi.org/10.3390/S20102990

Konfo, T. R. C., Djouhou, F. M. C., Hounhouigan, M. H., Dahouenon-Ahoussi, E., Avlessi, F., & Sohounhloue, C. K. D. (2023). Recent advances in the use of digital technologies in agri-food processing: A short review. *Applied Food Research, 3*(2), 100329. https://doi.org/10.1016/j.afres.2023.100329

Kumar, M. V., & Iyengar, N. C. S. (2017). A framework for blockchain technology in rice supply chain management. *Advanced Science and Technology Letters, 146*, 125–130.

Laaper, S., Fitzgerald, J., Quasney, E., Yeh, W., & Basir, M. (2017). Using blockchain to drive supply chain innovation. In *Digit. Supply Chain Manag. Logist. Proc. Hambg. Int. Conf. Logist.*, *1*(December), 2013.

Lei, M., Xu, L., Liu, T., Liu, S., & Sun, C. (2022). Integration of privacy protection and blockchain-based food safety traceability: Potential and challenges. *Foods, 11*(15), 2262. https://doi.org/10.3390/foods11152262

Levitt, T. (2016). *Blockchain technology trialled to tackle slavery in the fishing industry*. https://www.theguardian.com/sustainable-business/2016/sep/07/blockchain-fish-slavery-free-seafood-sustainable-technology

Li, R., Song, T., Mei, B., Li, H., Cheng, X., & Sun, L. (2019). Blockchain for large-scale internet of things data storage and protection. *IEEE Transactions on Services Computing, 12*(5), 762–771. https://doi.org/10.1109/TSC.2018.2853167

Longo, F., Nicoletti, L., & Padovano, A. (2020). Estimating the impact of blockchain adoption in the food processing industry and supply chain. *International Journal of Food Engineering*, *16*(5–6). https://doi.org/10.1515/IJFE-2019-0109/MACHINEREADABLECITATION/RIS

Manski, S. (2017). Building the blockchain world: Technological commonwealth or just more of the same? *Strategic Change, 26*(5), 511–522. https://doi.org/10.1002/jsc.2151

MarketsandMarkets Research. (2016). *Food traceability market worth $14 billion by 2019*. https://www.marketsandmarkets.com/PressReleases/food-traceability.asp. Accessed 5 Feb 2024

Maslova, A. (2017). *Growing the garden: How to use blockchain in agriculture*. https://cointelegraph.com/news/growing-the-garden-how-to-use-blockchain-in-agriculture. Accessed 5 Feb 2024

Mike Orcutt. (2017). *A blockchain for turkeys is more than a thanksgiving gimmick*. https://www.technologyreview.com/2017/11/23/147497/a-blockchain-for-turkeys-is-more-than-a-thanksgiving-gimmick/. Accessed 5 Feb 2024

Motta, G. A., Tekinerdogan, B., & Athanasiadis, I. N. (2020). Blockchain applications in the agri-food domain: The first wave. *Frontiers in Blockchain, 3*(February), 1–13. https://doi.org/10.3389/fbloc.2020.00006

Nakamoto S. (2008). *A peer-to-peer electronic cash system*. In: Bitcoin. http://nakamotoinstitute.org/bitcoin/

Novikova, L. Y., & Naumova, L. G. (2020). Dependence of fresh grapes and wine taste scores on the origin of varieties and weather conditions of the harvest year in the northern zone of industrial viticulture in Russia. *Agronomy, 10*(10 October), 1613. https://doi.org/10.3390/agronomy10101613

Oceana. (2013). *Oceana study reveals seafood fraud nationwide*. http://oceana.org/. Accessed 5 Feb 2024

Patel, A. S., Brahmbhatt, M. N., Bariya, A. R., Nayak, J. B., & Singh, V. K. (2023). Blockchain technology in food safety and traceability concern to livestock products. *Heliyon, 9*(6), e16526. https://doi.org/10.1016/j.heliyon.2023.e16526

Patel, D., Bothra, J., & Patel, V. (2017). *"Blockchain exhumed."* Asia Security and Privacy Conference.

Patidar, R., Agrawal, S., & Pratap, S. (2018). Development of novel strategies for designing sustainable Indian agri-fresh food supply chain. *Sādhanā, 43*(10), 1–16. https://doi.org/10.1007/S12046-018-0927-6

Patil, A. S., Tama, B. A., Park, Y., & Rhee, K. H. (2017). A framework for blockchain based secure smart green house farming. *Lecture Notes in Electrical Engineering, 474*, 1162–1167. https://doi.org/10.1007/978-981-10-7605-3_185

Pinna, A., & Ibba, S. (2018). A blockchain-based decentralized system for proper handling of temporary employment contracts. *Science and Information Conference*, 1231–1243.

Prashar, D., Jha, N., Jha, S., Lee, Y., & Joshi, G. P. (2020). Blockchain-based traceability and visibility for agricultural products: A decentralized way of ensuring food safety in India. *Sustainability, 12*(8), 3497. https://doi.org/10.3390/SU12083497

Provenance. (2016). *From shore to plate: Tracking tuna on the blockchain*. https://www.provenance.org/tracking-tuna-on-the-blockchain. Accessed 5 Feb 2024

Queiroz, M. M., Telles, R., & Bonilla, S. H. (2019). Blockchain and supply chain management integration: A systematic review of the literature. *Supply Chain Management, 25*(2), 241–254. https://doi.org/10.1108/SCM-03-2018-0143

Rejeb, A. (2018). Halal meat supply chain traceability based on HACCP, blockchain and internet of things. *Acta Technica Jaurinensis, 11*(4), 218–247. https://doi.org/10.14513/ACTATECHJAUR.V11.N4.467

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. *International Journal of Production Research, 57*(7), 2117–2135. https://doi.org/10.1080/00207543.2018.1533261

Sanjeev Kumar Sharma, V. S. (2020). *Applications of blockchain technology in the food industry*. https://www.newfoodmagazine.com/article/110116/blockchain/. Accessed 5 Feb 2024

Shafiee-Jood, M., & Cai, X. (2016). Reducing food loss and waste to enhance food security and environmental sustainability. *Environmental Science and Technology, 50*(16), 8432–8443. https://doi.org/10.1021/acs.est.6b01993

Shakhbulatov, D., Arora, A., Dong, Z., & Rojas-Cessa, R. (2019). Blockchain implementation for analysis of carbon footprint across food supply chain. *Proceedings - 2019 2nd IEEE International Conference on Blockchain, Blockchain 2019*, 546–551. https://doi.org/10.1109/BLOCKCHAIN.2019.00079

Sharma, S. (2017). Climate change and blockchain. *Available at SSRN 3088990*.

Shingh, S., Kamalvanshi, V., Ghimire, S., Basyal, S., & Dornean, A. (2020). Dairy supply chain system based on blockchain technology. *Asian Journal of Economics, Business and Accounting, 1*, 13–19. https://doi.org/10.9734/AJEBA/2020/V14I230189

Soil Association Certification. (2018). *Soil Association Certification*. https://www.soilassociation.org/certification/. Accessed 5 Feb 2024

Sustainable Shrimp Partnership. (2018). https://www.sustainableshrimppartnership.org/. Accessed 5 Feb 2024

Tharatipyakul, A., & Pongnumkul, S. (2021). User interface of blockchain-based agri-food traceability applications: A review. *IEEE Access, 9*, 82909–82929. https://doi.org/10.1109/ACCESS.2021.3085982

The Economist. (2015). *The great chain of being sure about things*. The Economist. https://www.economist.com/news/briefing/21677228-technology-behind-bitcoin-lets-people-who-do-not-know-or-trust-each-other-build-dependable. Accessed 5 Feb 2024

Tian, F. (2017). A supply chain traceability system for food safety based on HACCP, blockchain & Internet of things. *International Conference on Service Systems and Service Management, 2017*, 1–6.

Tripoli, M., & Schmidhuber, J. (2018). Emerging opportunities for the application of blockchain in the agri-food industry. *FAO and ICTSD: Rome and Geneva.*

United Nations World Food Programme (2017). *Blockchain Against Hunger: Harnessing Technology in Support of Syrian Refugees*. https://www.wfp.org/news/blockchain-against-hunger-harnessing-technology-support-syrian-refugees/. Accessed 5 Feb 2024

Wang, Y., Han, J. H., & Beynon-Davies, P. (2019). Understanding blockchain technology for future supply chains: A systematic literature review and research agenda. *Supply Chain Management, 24*(1), 62–84. https://doi.org/10.1108/SCM-03-2018-0148

Wass, S. (2017). *Global trade review*. https://www.gtreview.com/news/fintech/food-companies-unite-to-advance-blockchain-for-supply-chain-traceability/. Accessed 5 Feb 2024

Wognum, P. M., Bremmers, H., Trienekens, J. H., Van Der Vorst, J. G. A. J., & Bloemhof, J. M. (2011). Systems for sustainability and transparency of food supply chains - Current status and challenges. *Advanced Engineering Informatics, 25*(1), 65–76. https://doi.org/10.1016/j.aei.2010.06.001

Xu, Y., Li, X., Zeng, X., Cao, J., & Jiang, W. (2022). Application of blockchain technology in food safety control: Current trends and future prospects. *Critical Reviews in Food Science and Nutrition, 62*(10), 2800–2819. https://doi.org/10.1080/10408398.2020.1858752

Yiannas, F. (2018). A new era of food transparency powered by blockchain. *Innovations: Technology, Governance, Globalization, 12*(1–2), 46–56. https://doi.org/10.1162/inov_a_00266

Yu, M., & Nagurney, A. (2013). Competitive food supply chain networks with application to fresh produce. *European Journal of Operational Research, 224*(2), 273–282. https://doi.org/10.1016/j.ejor.2012.07.033

Zeto. (2018). *Zetochain*. https://www.zeto.ie/. Accessed 5 Feb 2024

Zhao, G., Liu, S., Lopez, C., Lu, H., Elgueta, S., Chen, H., & Boshkoska, B. M. (2019). Blockchain technology in agri-food value chain management: A synthesis of applications, challenges and future research directions. *Computers in Industry, 109*, 83–99. https://doi.org/10.1016/j.compind.2019.04.002

Zhu, Z., Chu, F., Dolgui, A., Chu, C., Zhou, W., & Piramuthu, S. (2018). Recent advances and opportunities in sustainable food supply chain: A model-oriented review. *International Journal of Production Research, 56*(17), 5700–5722. https://doi.org/10.1080/00207543.2018.1425014