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Blockchain technology characteristics essential for the agri-food sector: A systematic review

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ABSTRACT

Blockchain is seen as a disruptive fundamental technology that will transform agri-food sectors in the near future. Blockchain is a digital, immutable, decentralized ledger of transactions that is replicated and distributed throughout the chain of computer systems on the blockchain's network. This systematic review examines the literature to identify the enabling characteristics of blockchain technology that support its application in the agri-food sectors. The literature reviewed indicated essential characteristics such as transparency, immutability, redundancy, versatility, automation, and remittance. Among these features, immutability and automation have a salient role in the current implementation, particularly in food traceability. However, the application of blockchain in the agri-food sector is not without controversies. More research is needed regarding technical improvement and its environmental impact.

1. Introduction

1.1. Background

Recently we have witnessed an upsurge of interest in blockchain technology and its likely applications across a range of industrial domains (Beck, Müller-Bloch, & King, 2018; Lockl, Schlatt, Schweizer, Urbach, & Harth, 2020). Blockchain is a digital, immutable, decentralized ledger of transactions (Friedlmaier, Tumasjan, & Welpe, 2018; Hackius & Petersen, 2017) that is replicated and distributed throughout the chain of computer systems on the blockchain's network (Iansiti & Lakhani, 2017; Tayeb & Lago, 2018, pp. 34–43; Xiong, Dalhaus, Wang, & Huang, 2020). A blockchain-based system aims to shift the focus of trust-building from institutions toward immutable algorithms (Nakamoto, 2008) through the enhanced security of data management and process application logic (i.e., smart contracts) (Labazova, Dehling, & Sunyaev, 2019).

Both practitioners and researchers are increasingly examining the potential of blockchain technology beyond its application in cryptocurrencies (Beck et al., 2018; Fridgen et al., 2018; Labazova et al., 2019). Blockchain technology also holds the promise of revolutionizing the agriculture and food production sectors through improved food supply chain management, developing smart agriculture, and utilizing decentralized insurance systems (Duan, Zhang, Gong, Brown, & Li, 2020; Lin et al., 2020; Torky and Hassanein, 2020; Xiong et al., 2020). Some of the recent blockchain platforms in smart agriculture are Provenance (supply chain traceability), AgriDigital (supply chain management), IBM Blockchain (agricultural logistics), Foodcoin (transaction management), AppliFarm (animal welfare traceability) (for details refer to e.g., Torky & Hassanein, 2020). Yet, a large number of the present blockchain projects remain at the concept level and fail to move to production use (Condos, Sorrell, & Donegan, 2016; Labazova et al., 2019). Part of this failure is attributed to the challenges concerning the scalability of narrow-scope prototypes and the lack of computational properties essential for efficient consensus mechanisms (Sylvester, 2019; Xu, Weber, Staples, Zhu, Bosch, Bass, Pautasso, & Rimba, 2017; Yli-Huumo, Ko, Choi, Park, & Smolander, 2016). Furthermore, most of the current blockchain-based system designs are based on trial-and-error approaches (Furlonger & Valdes, 2017) and more empirical evidence is needed to be developed based on blockchain characteristics essential for agri-food systems (Dey & Shekhawat, 2021; Labazova et al., 2019).

Several reviews have explored the potential of blockchain technology in transforming the agriculture sector (for a summary of reviews see Appendix Table A3). Extant reviews provide insightful perspectives on

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diverse blockchain applications in agriculture and food systems (e.g., Alobid et al., 2018, 2022; Demestichas, Peppes, Alexakis, & Adamopoulou, 2020; Yadav & Singh, 2019) an overview of challenges (e.g., da Silveira, Lermen, & Amaral, 2021; Li, Lee, & Gharehgozli, 2021; Pandey, Pant, & Snasel, 2022; Vu, Ghadge, & Bourlakis, 2021). For instance, Feng, Wang, Duan, Zhang, and Zhang (2020) delved into the functionalities of blockchain technology, emphasizing the advantages and challenges linked to the adoption of traceability systems built on blockchain. Rana, Tricase, and De Cesare (2021) reviewed the applications of blockchain technology in the context of a sustainable agricultural and food supply chain. Yet a critical assessment of blockchain characteristics underpinning this intervention remains fragmented across the literature (Labazova et al., 2019). Additionally, while prior reviews have mainly focused on theoretical benefits and conceptual frameworks, practical implementations remain underexplored.

More knowledge concerning blockchain characteristics is crucial in fulfilling expectations for the successful development of blockchain-based systems relevant to the agri-food domain (Bermeo-Almeida et al., 2018; Labazova et al., 2019; Zhao et al., 2019). Therefore, this review aims to identify and critically evaluate characteristics of blockchain that support its application in the agri-food sector and analyze the efficacy of these characteristics. We focused on empirical use cases and, hence, discussions of technical features and conceptual developments are out of the scope of this review. By highlighting the specific features of blockchain that support its applicability in the agri-food industry, this review not only consolidates existing knowledge but also serves as a new contribution to progress in this field. The results of this systematic review are suitable to inform and guide future research efforts focused on the implementation of blockchain-based solutions in the agri-food sector.

Section two presents concepts and structures of typical blockchain technology. In section three our method for data collection and analysis is presented. Section four provides results on the analysis of key characteristics that fit with current blockchain-based systems employed in the agriculture and food industry. The paper concludes with a brief discussion of the theoretical significance, practical implications, and limitations for future research.

1.2. The concept of blockchain technology

1.2.1. Overview and definitions

A blockchain is essentially a form of distributed ledger system wherein a series of data blocks (transactions) relate to each other with algorithms of cryptographic hashing to ensure reliability and integrity (Van Wassenaer, van Hilten, van Ingen, & van Asseldonk, 2021). As depicted in Fig. 1, each block consists of two core components, namely the header and the main data (Liang, 2020). The main data includes records of transaction data, whilst the header comprises a summary hash of all transactions (known as the 'Merkle Root'), a hash of the current and previous block, timestamp, nonce, and other information (Liang, 2020).

A cryptographic hash is a mathematical algorithm that converts input data into a fixed-size output of enciphered numbers known as a 'hash' value (Van Wassenaer et al., 2021). Hash values are used to link a block to the previous blocks. Hash values are irreversible and unique, ensuring the integrity and immutability of data in the blockchain (Van Wassenaer et al., 2021). The fundamental component of blockchain is the Merkle tree, which is built on cryptographic hash functions (Chen, Chou, & Chou, 2019). Each block records transactions in the form of binary data structures (known as a Merkle tree). The hashes of sub-nodes are merged into the upper node's header, and this pattern continues iteratively until it reaches the root node. The root node works as a shortened identifier for the whole tree, comprising all the information (Chen et al., 2019).

Broadly, there are three main forms of blockchain depending on access control conditions; these are public (permissionless, e.g., Ethereum), private (permissioned, e.g., Hyperledger), and hybrid (public permissioned) blockchains (Gramoli, 2016). Peer participation in the blockchain system needs to be defined as either open or alliance (Böhme, Christin, Edelman, & Moore, 2015; Yermack, 2017), (such as Internet of Things (IoT) devices, or other blockchain systems) needs to be specified (Niranjanamurthy, Nithya, & Jagannatha, 2019).

1.2.2. Distributed consensus mechanisms

Consensus mechanisms (or algorithms) are employed to verify transactions and ensure the security of the underlying blockchain data (Demestichas et al., 2020). Transactions are documented as a data block (see Fig. 1), that must first pass independent peer-to-peer network verification before being included in the blockchain network. This mechanism tackles the issue of 'double-spending' (sharing the same input) and protects the blockchain from fraudulent activities (Lin et al., 2020).

There are different types of consensus mechanisms, but two of the most widely used consensus protocols are Proof of work (PoW) and proof of stake (PoS). Proof of work (PoW) is a decentralized consensus protocol that forces network participants to expend effort to solve random complex computational puzzles (Lin et al., 2020). The first to develop the solution ('hash') receives the right to form the new block and validate the transaction. In PoS, rather than using a competitive rewards-based mechanism, a specific number of validators are designated randomly to approve transactions and confirm block data (Demestichas et al., 2020).

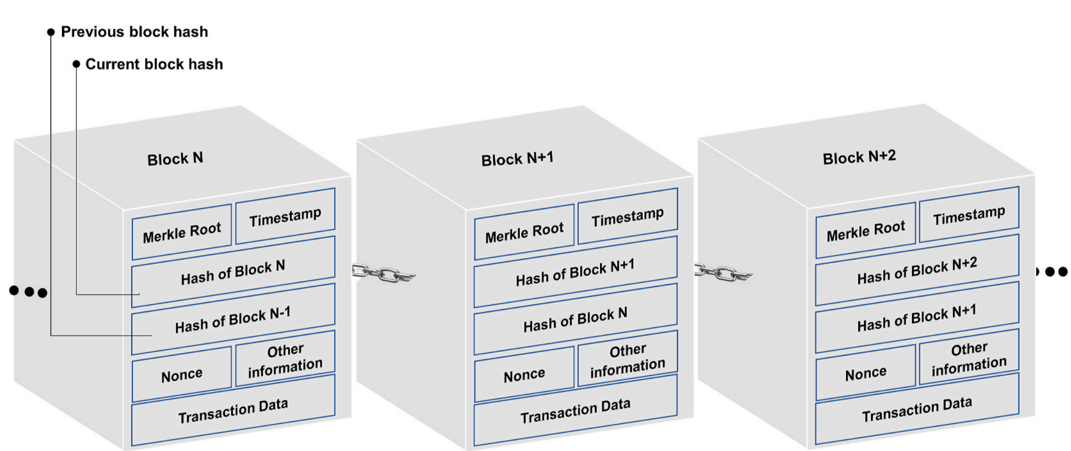

Fig. 1. Thematic representation of the structure of a blockchain (see e.g., Chen et al., 2019). Every block contains a cryptographic hash of the previous block, a timestamp, and transaction data (often embodied as a Merkle tree).

1.2.3. Smart contracts

Smart contracts are self-executing script programs that are deployed in blockchains, containing a tamper-proof logic code, that implements once predetermined conditions are met (Demestichas et al., 2020). They are intended to automatically execute, control or document events and transactions following the terms of an agreement. This will ensure the network members immediately of the outcome, rendering the need for the intermediary's involvement (Demestichas et al., 2020). A smart contract links the blockchain to real-world events, automates workflows, and allows integration with IoT devices. For instance, scanners and sensors function on a food shipment and transmit data to the smart contract on a blockchain that then executes payment to the specified supplier. For another example, an Internet of Things (IoT) device can capture a wide range of valuable data to be processed through an Artificial Intelligence (AI) system. The output data generated by the AI system then activates smart contracts automatically.

2. Materials and methods

We have conducted a systematic review to provide new scientific insights into the application of blockchain in the agricultural sector. A systematic literature review collates empirical evidence, critically appraises, and extracts and synthesizes data, ensuring a rigorous evidence-focused answer to the predefined research question (Khan, Kunz, Kleijnen, & Antes, 2003; Mallett, Hagen-Zanker, Slater, & Duvendack, 2012; Waddington, White, Snilstveit, Hombrados, Vojtkova, Davies, Bhavsar, Eyers, Koehlmoos, Petticrew, Valentine, & Tugwell, 2012). The review was performed based on a protocol for identifying, screening, and evaluating the eligibility of articles, as illustrated in Fig. 2, following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) reporting approach (Moher, Shamseer, Clarke, Ghersi, Liberati, Petticrew, Shekelle, & Stewart, 2015; Xhakollari, Canavari, & Osman, 2019; Zarba et al., 2022).

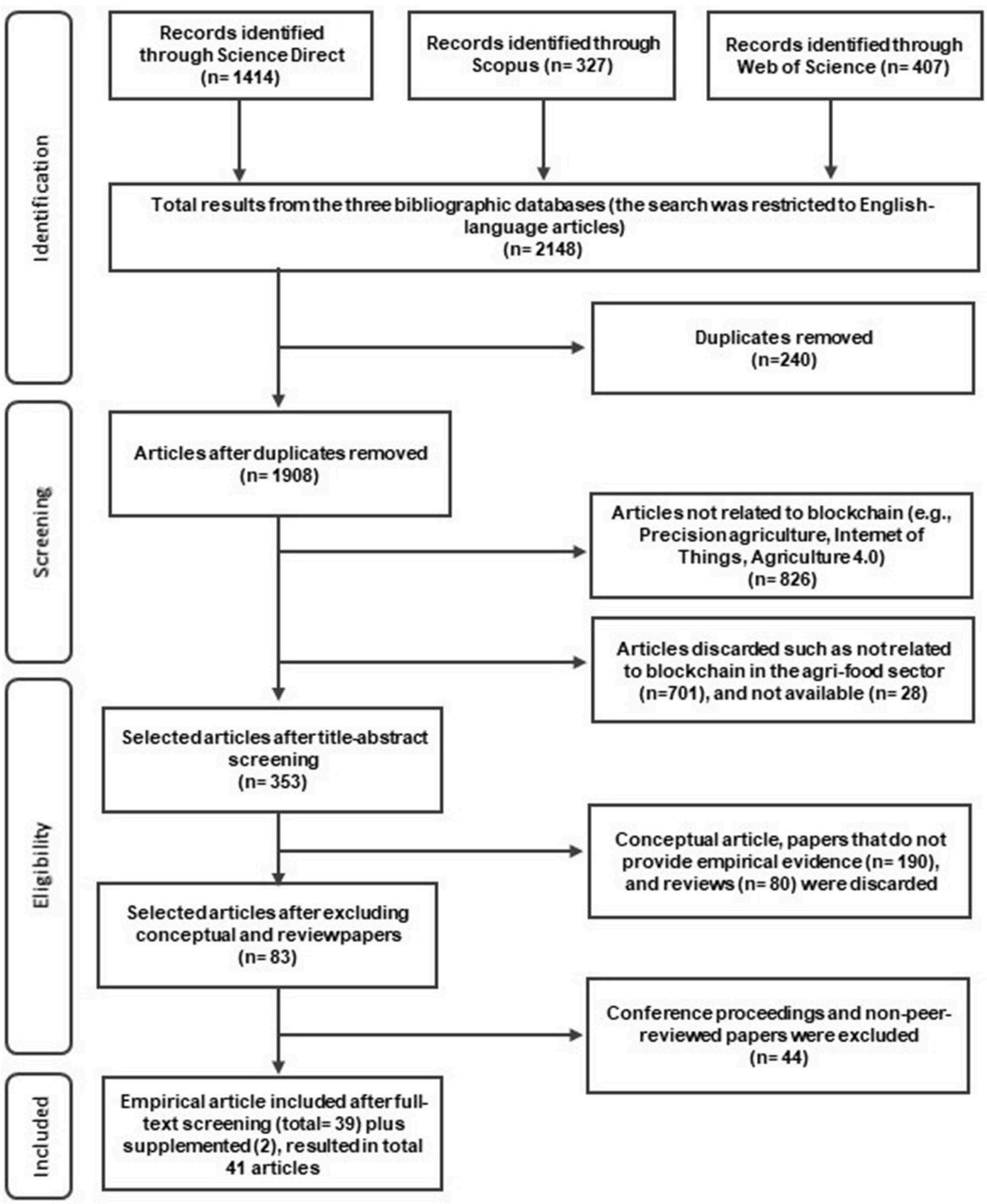

Fig. 2. Flow diagram of included and excluded studies in the review.

2.1. Search strategy

In August 2021, a literature search was conducted using Science Direct, Web of Science, and Scopus electronic databases. The search was delimited to include papers published between 2017 and 2021, with papers before 2017 not considered to ensure the incorporation of recent findings. These databases were particularly appropriate to the scope of the current systematic review owing to their extensive coverage and content quality (Clark, Stewart, Panzone, Kyriazakis, & Frewer, 2017; Siva et al., 2016; Yadav & Singh, 2019). The following search query was used for the title, abstract and keywords through each database: TITLE-ABS-KEY ((Blockchain) AND (Agriculture* OR Agricultural* OR Agribusiness* OR Farming* OR Food*)). Overall, the literature searches of the three databases resulted in 1414 articles from Science Direct (1149 research and 265 review articles), 327 articles from Scopus (285 research and 42 review articles), and 407 articles from Web of Science (344 research and 63 review articles), (see Fig. 2).

2.2. Study selection and exclusion criteria

Obtained articles from three databases (n = 2148) were imported into Endnote (version X9.3; Thomson Reuters), 240 duplicates were manually removed, and 1908 articles were included in the initial list (see Fig. 2). Titles and abstracts were screened for the relevance of included articles. After screening based on title and abstract, 1555 articles were discarded that were not related to the application of blockchain in the agri-food sector (e.g., blockchain-related research papers but not in the agri-food sector or papers focusing on other aspects of precision agriculture, such as Agriculture 4.0 and Internet of Things). The resulting 353 articles were assessed against inclusion criteria (Table 1), and 314 were discarded. Excluded papers include research articles without empirical evidence of blockchain-based agri-food use cases (e.g., conceptual papers, papers suggesting only frameworks, reviews, and non-peer-reviewed articles. It should be noted that there are also several papers examining applications of blockchain for the conservation of biodiversity under threat from climate change (e.g., Chen, 2018; Dona, 2019; Hartmann & Thomas, 2020; Howson, 2019; Kouhizadeh & Sarkis, 2018), water management (e.g., Pincheira, Vecchio, Giaffreda, & Kanhere, 2021), and land registration (e.g., Barbieri & Gassen, 2017) which were considered irrelevant for this review. Eligibility evaluation of the remaining articles was carried out independently by two of the authors (for detailed documentation refer to Van Wassenaer et al., 2021). Overall, a high inter-rater agreement was achieved, and discrepancies between the evaluators were resolved through discussion until a consensus was reached. Ultimately, 39 papers were appraised as being eligible for full-text review. Included articles were screened for cross-references and an additional 2 articles were supplemented, resulting in 41 articles in total (see Table A1 in the Appendix).

2.3. Study characteristics

To uncover the unique enabling characteristics of blockchain technology implemented in the agri-food sector, the resulting 41 peer-reviewed empirical articles are utilized to develop concept-centric (Webster & Watson, 2002) summary tables (See Tables 2–4), thereby synthesizing the literature at hand.

General information (author, year, country), intervention characteristics (e.g., use cases, purpose), and outcome characteristics (empirical results obtained) from all the included articles were extracted and listed in Table A1 (Appendix).

3. Results

In this section, we present the outcomes of our literature review on blockchain characteristics with potential use in the agri-food industry. We start by presenting a bibliographic analysis followed by a demonstration of the main agri-food use cases across the retrieved articles. Finally, we have presented the outcome of our literature review by mapping blockchain characteristics in the agri-food domain.

3.1. Bibliographic analysis

The blockchain was conceptualized in 2008 but was popularized in 2016, primarily within financial services (Narayanan, Bonneau, Felten, Miller, & Goldfeder, 2016). As indicated in Fig. 3, interest in blockchain technology and its potential advantages in the agri-food sector has been rising among scholars, causing the literature on this technology to grow rapidly in recent years (see also Howson, 2020; Motta, Tekinerdogan, & Athanasiadis, 2020). The period from 2017 to 2018 is considered an important phase of conceptual exploration of blockchain potential in the agri-food sector and during 2019–2020 increasing use cases were examined in this sector (Ge, Brewster, Spek, Smeenk, Top, van Diepen, Klaase, Graumans, & de Wildt, 2017; Kamilaris, Fonts, & Prenafeta-Boldú, 2019; Van Wassenaer et al., 2021). Nevertheless, most of the applications are pilot schemes that are still ongoing or have stopped at the proof-of-concept phase (Van Wassenaer et al., 2021).

Fig. 4 represents the share of research articles from the retrieved literature and the distribution of peer-reviewed articles with agri-food use cases (n = 41). This review centred on articles with empirical evidence of applications for blockchain technology in the food and agriculture sectors. As can be seen from Fig. 4, most agri-food blockchain implementations are related to traceability and food authentication. Other areas, such as farm management and e-commerce, have also gained momentum in the last two years.

Figs. 5 and 6 present the distribution of agri-food use cases across countries, and across journals, respectively. What is clear is that most of the studies on this subject were conducted in Asian countries, especially China and India, which have focused on the application of blockchain technology in agriculture (also pointed out in Ronaghi, 2021). Among European countries, Italy is pioneering in the development of agri-food

Table 1
Inclusion and exclusion criteria.

Inclusion criteria
• Full-text papers with a focus on agriculture and food supply chain use cases
• Full-text research papers presenting original empirical evidence of implementing blockchain-based systems
• Full-text papers published in a peer-reviewed journal
• Full-text papers written in English
Exclusion criteria
• Research papers that are not related to the application of blockchain in the agri-food system
• Papers that do not include original empirical results (e.g., reviews, opinion papers and outlooks, discussion papers, etc.)
• Papers discussing conceptual and theoretical aspects of blockchain technology
• Conference proceedings, book chapters, unpublished theses, reports, and white papers
• Papers focusing on other aspects of precision agriculture, such as Industry 4.0 and the Internet of Things (IoT).
• Papers concerning the application of blockchain for water management, land registration, and climate change adaptation and biodiversity conservation.
• Papers published before 2017

Table 2
Summary of evidence of the 'trust evoking' features of blockchain-based use cases in the agri-food domain.

Feature	Sub-feature	Authors	Key Findings
Transparency	**Shared and public interaction** (Keywords incl. shared, public access)	Zhang et al. (2021)	Adopting the IoT-based blockchain traceability system for frozen aquatic products, enabled participants to share more reliable tracing information.
		Guido et al. (2020)	The blockchain-based framework for tracing the extra-virgin olive oil supply chain increased the perceived value of the product, and the information shared can be easily used by other companies.
		Kamble et al. (2020)	Secure and decentralized sharing of data in agriculture supply chain increased trust and transparency.
		Longo et al. (2020)	The suggested blockchain platform improves sharing information along the dairy supply chain up to consumers. All transactions are documented in a product's history from production to final sale.
		Tönnissen and Teuteberg (2020)	Blockchain possibilities for logistics and supply chain management have led to various applications. However, successful implementations require a large number of stakeholders in the global logistic chains to participate and use the blockchain-based applications (hence not necessarily resulting in reduced intermediaries).
		Violino et al. (2020)	Proposed a blockchain prototype for traceability of the virgin olive oil supply chain. The proposed prototype provides product authenticity information to the consumers. Consumers can scan the QR code with their smartphones to receive a digital number along with the product information.
		Malarvizhi (2019)	The proposed model facilitates shared transaction information across all nodes which improves transparency in the various manufacturing processing of edible palm products.
	Low friction in providing information (keywords incl. information smooth flow, reduce asymmetry)	Tsolakis et al. (2021)	One of the main challenges in the fish industry is the information asymmetry and inconsistencies in data structures across the distributed data sources. The use of a blockchain-based supply system led to a unique opportunity to secure shared information and prevent unregulated (or unreported) fishing operations (through principles of data archetypes, data capture, data consistency and data interoperability).
		Bumblauskas et al. (2020)	Blockchain platform for egg traceability within the distribution chain improved information exchange between producer and consumers. This system enabled consumers to make more informed food decisions.
		Chen et al. (2020)	Demonstrated that blockchain based systems can resolve the asymmetric information problems in organic food systems.
		Ferdousi et al. (2020)	In the suggested blockchain-based supply chain framework, owners of animals could access data at any time. They also had the possibility to make necessary decisions regarding how long the data needed to be stored or shared with other farm owners.
		Kumar et al. (2020)	A blockchain-based system to improve food supply chain management developed using Internet of things for collecting and transferring information on the blockchain platform. This system accelerated the flow of information and enhanced the delivery of real-time food safety information to the network participants.
		Liu et al. (2020)	The demand estimation before and after adopting of blockchain-enabled big data will reduce demand information asymmetry and will lead to increased trust in agri-food safety

(continued on next page)

Table 2 (*continued*)

Feature	Sub-feature	Authors	Key Findings
			information communicated between producers and retailers.
		Zhang (2020)	Designed blockchain-based mechanism of grain supply chain creates a consistent flow of shared information across channels.
		Zhang, Sun, et al. (2020)	Compared to existing models for grain supply chain management, the proposed blockchain based system provides a secure platform for real-time information interconnection regarding hazardous materials across supply chain.
Immutability	**Peer verification of transaction** (Keywords incl. peer verification, consensus mechanism)	Cao et al. (2021)	A blockchain-based beef supply chain system in which data (e.g., animal breed and the types of feed) was reconciled and verified through the multi-sig authenticates system (requires multiple signatures to execute a transaction) across the network to ensure shared responsibilities. The peer verification of information across networks resulted in improved trust in the cross-border beef supply chain.
		Ferdousi et al. (2020)	The suggested smart blockchain-based supply chain framework for trading of livestock led to faster data verification without requesting data from independent local databases. This framework employed proof of authority (PoA) to achieve consensus and allow the running of complex smart contract functions.
		Yang et al. (2021)	The consensus mechanism ensures that the participating nodes in the blockchain network keep consistent information, and additional blocks are accurately included in the network.
		Zhang et al. (2021)	Aquatic feed quality information was logically segmented and reliably stored on-chain peer nodes after the process of verification and consensus was achieved.
		Rogerson and Parry (2020)	The findings from the case studies demonstrated that blockchain most likely increases visibility and trust in supply chain management. It also reduces the risk of human error and counterfeit goods. However, in practice, development of blockchain-based solutions with full transparency can be costly.
	Enhanced security through cryptography (keywords incl. cryptography, tamper proof architecture, immutability, hash algorithms, time-stamped)	Cao et al. (2021)	Authors examined a blockchain-based beef supply chain system and concluded that it was technically feasible to obtain a 'human-machine reconcile mechanism' using cryptographically secured data.
		Chen et al. (2020)	As part of its "democratization" characteristics, the proposed blockchain-based system provided anonymity, transparency, autonomy, and tamper-proofing.
		Feng, Wang, Duan, et al. (2020)	The blockchain model reduced the risk of product losses and improved quality data management of frozen shellfish during cold storage.
		Zhang et al. (2021)	System reliability increased due to an on-chain verification mechanism by preventing the unauthorized uploading of data and even depositing of false data by legitimate users.
		Grecuccio et al. (2020)	Suggested traceability blockchain-based systems for fish supply chain prevents tampering with tracking information.
		Guido et al. (2020)	A proposed tracking blockchain model for olive oil can be easily adopted by small enterprises. In addition to optimizing traceability, the proposed framework also ensures the truthfulness of the product information delivered to the consumers.
		Ferdousi et al. (2020)	Cryptographic hashes were computed for both transactions and smart contracts,

(continued on next page)

Table 2 (*continued*)

Feature	Sub-feature	Authors	Key Findings
			ultimately increasing information security.
		Hang et al. (2020)	The cryptography structure employed in the blockchain-based fish farm system led to higher security and user accountability.
		Tan et al. (2020)	The proposed blockchain-based dairy traceability reduced the risks of human error or tampering with information and therefore improved the food safety and prevented food frauds.
		Tsolakis et al. (2021)	The use of cryptographic technology in the suggested fish farming industry increased efficiency by reducing audit and certification costs.
		Yang et al. (2021)	Blockchain technology together with the cryptography mechanism employed in the proposed model improved the safety of sharing private information within the network.
		Zhang, Han, et al. (2020)	The blockchain architecture for storing high-throughput crop breeding data ensured breeding data transmission and security by cryptography.
		Zhang, Sun, et al. (2020)	The suggested framework benefited the privacy protection module including the encryption (encoding data using mathematical algorithms) and decryption of private information (transforms encrypted data into its original format), which ensures data storage security.
		Malarvizhi (2019)	The proposed blockchain model contains an encrypted database with tamper-proof algorithms available to all participants (i.e., nodes including wholesale traders, retailers, and consumers) in the palm chain. Transaction data is encrypted and stored in blocks which are shared across all nodes. This led to improved transparency in the various stages of producing palm products throughout the chain, including collection of commodities, chilling, packaging, labeling, and transporting. The use of this technology increases the added value as well as the value of the domestic and export markets due to enhanced standardization, differentiation, and food safety.
		Violino et al. (2019)	Traceability blockchain-based systems had tamper-proof function in the olive supply chain that improved immutability.
		Leng et al. (2018)	Proposed a dual-chain agricultural business resource public blockchain (employing separate chains of ‘user information chain’ and ‘transaction chain’). The authors concluded that the model ensures the transparency and security of transaction information as well as maintaining the privacy of enterprise information.
		Ferdousi et al. (2020)	A private blockchain network is configured so that outsiders cannot generally access the network without proper authorization.

blockchain implementation. Across journals, the Journal of Cleaner Production, and the Institute of Electrical and Electronics Engineering, had the highest number of publications, followed by the International Journal of Information Management, and Computers and Electronics in Agriculture.

3.2. Mapping blockchain characteristics in the agri-food domain

This section examines the literature to identify the blockchain characteristics which may be potentially relevant for the agri-food sector. Reviewing the included articles indicated that enabling characteristics of blockchain for agriculture can be broadly categorized as 1) trust-evoking characteristics, 2) decentralized features, and 3) the ability to integrate with other digital platforms. Fig. 7, depicts a summary of relevant enabling features of blockchain technology in the agri-food domain, based on the reviewed articles. Keywords and definitions used for categorizing these features are presented in Table A2 (see Appendix). In the following sections, we provide examples of different blockchain characteristics essential for the development of agri-food applications (detailed analyses are provided in Tables 2–4).

3.2.1. The impact of trust evoking

In today’s digital era, access to information, and control of its flow, is reshaping established trade conventions. The use of the internet and digital technologies is increasingly integrated into daily transactions in the agri-food supply chain. The explosion of the internet and the use of online technologies in agri-food production have provided advantages but have also led to immense risks in data security (Shyamasundar &

Table 3
Summary of evidence of 'decentralization' features of blockchain-based use cases in agri-food domain.

Sub-feature	Sub'-feature	Authors	Key Findings
Redundancy	**Distributed ledger** (keywords incl. reliability, redundancy, distributed)	Zhang et al. (2021)	Data recorded on distributed ledgers (by utilizing a smart contract and consensus mechanism) can support different levels of traceability services.
		Ferdousi et al. (2020)	The redundancy introduced by the Ethereum blockchain can mitigate the problem of 'single point of failure' associated with traditional server-centric systems.
		Garrard and Fielke (2020)	Investigated the potential of a blockchain ledger to enable product tracking in the prawn aquaculture industry. Authors did not find significant gains in using the blockchain based ledger in product tracking, although it helped to digitize the operations.
		George et al. (2019)	The decentralized nature of the blockchain increases security and efficiency of quality controls.
		Kamble et al. (2020)	The distributed ledger is an important and crucial feature of blockchain in the agricultural supply chain traceability. The authors concluded that the integrated application of IoT and blockchain had the potential to transform an agri-food system into a data-driven sustainable supply chain.
		Köhler and Pizzol (2020)	Blockchain technology offers applications in food supply chains owing to their decentralization of information and immutability mechanisms that increase transparency, traceability, and eventually trust. Though, plausible evidence does not exist supporting other impacts, such as increased sustainability and improved data management.
		Liu et al. (2020)	The blockchain decentralization feature in the proposed information service framework for the green food supply chain can improve data quality and value. The price in the decentralized decision-making condition was higher than the centralized decision-making conditions, but income in centralized decision-making conditions was higher than decentralized decision-making conditions.
		Li et al. (2020)	The results of the study comparing blockchain-based e-commerce with the traditional electronic-agriculture system revealed that decentralized blockchain-based e-commerce provides great convenience to farmers and accelerates the development of sustainable smart agriculture.
Versatility	**Anonymity of participants** (Keywords incl. anonymity)	Ferdousi et al. (2020)	The proposed framework for the beef cattle supply chain supports anonymity for the users to protect identities in transferring animal-related data to new owners.
	Open source (Keywords incl. scalability, peers' participation in development)	Cao et al. (2021)	The suggested framework did not require central control of the supply chain and is open to participation from multiple tiers of actors and external organizations.
		Yang et al. (2021)	The open source blockchain model allowed users to perform performance tests on the blockchain network through predefined use cases. The model included a reputation-based smart contract (i.e., using incentive mechanism) to ensure peer participation in sharing data.
		Kumar and Iyengar (2017)	The decentralized system based on a blockchain framework improved product safety in a rice supply chain management.
		Kumar et al. (2020)	A blockchain-based supply management system was developed, where each participant could add, update, and check production information. Any flaw in the transaction among participants can be easily identify in real time.

Patil, 2018). Despite significant efforts to tackle the issue of trade security and privacy, there have always been problems of information leaks due to the presence of third parties or the manipulation of data by unscrupulous business partners (Fang et al., 2020; Shyamasundar & Patil, 2018). Thus, one of the challenging quests within the agri-food sector has been to construct a trust protocol across the supply chain.

The blockchain ledger is a database of appended transactions that reflects blocks of data verified by the network. The blockchain protocol allows peer members of the network to access these verified transactions at any given time. Members can trust the integrity of the data as it is not

Table 4
Summary of evidence of 'system integration' features of blockchain-based use cases in agri-food domain.

Sub-feature	Sub'-feature	Authors	Key Findings
Automation	**Use of smart contracts** (keywords incl. smart contracts, automation)	Tsolakis et al. (2021)	An authentication process can be accomplished by creating a protocol to verify seafood storage temperatures with a smart contract.
		Yang et al. (2021)	A platform composed of smart contracts enables different business functions including uploading data by enterprises at different nodes and querying traceability data by consumers as well as authorities.
		Zhang et al. (2021)	Deployed smart contracts and consensus strategy in the blockchain traceability system significantly improved the quality and safety of the frozen aquatic product.
		Ferdousi et al. (2020)	The proposed framework employed proof of authority (PoA) to achieve consensus and allow the running of complex smart contract functions.
		Köhler and Pizzol (2020)	Smart contracts automatically enforce agreements and payments, or other legal obligations, thereby removing the need for trusted third parties.
		Hang et al. (2020)	Automated use of smart contracts in a blockchain-based fish farm platform reduced the risk of error and manipulation.
		Casino et al., (2021)	The automation provided by smart contracts in suggested traceability architecture reduced costs in the dairy food supply chain.
		Zhang, Sun, et al. (2020)	The information processing mechanism of the suggested blockchain based platform for grain supply chain management is realized through two different types of smart contracts.
		Salah et al. (2019)	The proposed Ethereum blockchain model builds on the utilization of smart contracts to record interactions which increased the transparency and efficiency of soybean transactions across the supply chain network.
		Mao et al. (2018)	Smart contracts enable efficient automation in blockchain-based solutions.
	Platform for real-time integration (Keywords incl. IoT, RFID, sensors, etc.)	Cao et al. (2021)	The proposed model using wireless RFID sensors and IoT equipment improved the beef supply chain management.
		Yang et al. (2021)	The platform allowed users to track relevant information in real-time, such as the number of nodes, contracts, and transactions.
		Alonso et al. (2020)	The smart farming platform developed an integration of blockchain and IoT devices to monitor the state of dairy cattle and feeds level in real time. The tamper-proof framework ensured the traceability of all the information in systems and enabled sharing of reliable, secure, and transparent information.
		Bumblauskas et al. (2020)	Internet of Things technology combined with blockchain to track eggs within the distribution chain in real-time.
		Casino et al. (2021)	The self-executing capacities of smart contracts ensured redundancy with real-time synchronization of the communicated data.
		Chen et al. (2020)	The blockchain network collects and loads real-time data using smart devices, which solves asymmetric information problems and organic food tracking.
		Feng, Wang, Duan, et al. (2020)	A blockchain-based multi-sensors monitoring system with HACCP food safety measures provided real-time reliable information of shellfish quality during cold storage.
		Iqbal and Butt (2020)	The blockchain architecture provides a platform for sharing reports in a notification system after consensus among

(continued on next page)

Table 4 (*continued*)

Sub-feature	Sub'-feature	Authors	Key Findings
			farmers, regulators, and distributors.
		Kamble et al. (2020)	Blockchain technology manages transaction processes on a real-time basis in the agricultural supply chain.
		Liu et al. (2020)	The fusion of blockchain and Big Data resulted in more consistently accurate and reliable information communication of the food safety between retailers and producers.
		Nesarani et al. (2020)	The suggested remote monitoring system for optimum agricultural production through the integration of blockchain and IoT technologies provides real-time data transmission to farmers and all stakeholders involved.
		Tsolakis et al. (2021)	Blockchain-based automation (e.g., using RFID e-tagging and scanning of fish, sensors, and on-line cameras, monitoring devices for detecting by-catches, and smart weighting system) can reduce unregulated fishing operations.
		Zhang, Sun, et al. (2020)	The designed blockchain storage mechanism of grain supply chain technology enabled real-time sharing of hazardous-material information.
		Zhang et al. (2021)	Real-time tracking was achieved through IoT integration in the blockchain traceability system for frozen aquatic products.
		Surasak et al. (2019)	Blockchain integration with IoT improves security of the real-time data in the traceability system.
		Tian (2017)	By incorporating IoT and wireless sensors in a warehousing center, the real-time storage information of the product, including quantity, temperature, humidity, and storage time, can be checked and updated in both the product's profile and Tag.
Remittance	**Faster settlement** (Keywords e.g., using cryptocurrency, fast settlement)	Li et al. (2020)	Statistical analysis indicated that blockchain based e-commerce provides great convenience to farmers, increasing trade by 25% on average over traditional e-agriculture, which can accelerate the development of sustainable smart agriculture.
		Longo et al. (2020)	Ethereum blockchain-enabled dairy supply chain monitoring can provide advantages with a minimal impact on the product's consumer price; however, the costs will increase as we move down the supply chain.
		Ferdousi et al. (2020)	The proof of authority (PoA) consensus mechanism employed in the proposed framework improved the transaction settlement by eliminating expensive hash computations.
	Lower transaction fee (Keywords e.g., lower transaction fee)	Syromyatnikov et al. (2020)	Examined agile supply chain management methods by using blockchain technology. The authors concluded that the use of blockchain technology leads to a reduction in transaction costs due to more efficient interactions between producers, consumers, and intermediaries in the flow of goods and services through the supply chain.
		Kamble et al. (2020)	This study highlighted that while blockchain technology offers potential for improving traceability in the agriculture supply chain, its impact was found to be limited by high implementation costs and the lack of technical expertise among stakeholders.
		Morya et al. (2020)	Despite the possibilities of blockchain improving agri-food efficiency, current blockchain implementations still have problems such as lack of computing resources, scalability issues, and relatively higher transactions costs.
		Tan and Ngan (2020)	The use of IoT sensors and smart contracts led to reduced

(*continued on next page*)

Table 4 (*continued*)

Sub-feature	Sub'-feature	Authors	Key Findings
			transaction time and costs in transactions between dairy producers and wholesalers or retailers.

feasible to alter any verified stored data (Köhler & Pizzol, 2020; Kshetri, 2017). To ensure the non-repudiation of information in a blockchain structure (in which participants cannot deny the transaction), security mechanisms, such as digital signature (Aki, 1983), identity authentication, and time stamping (Israeli & Li, 1987), are employed (for technical details refer to the review by Fang et al., 2020). As a result, these configurations give transactions transparency and immutability (Shyamasundar & Patil, 2018).

3.2.1.1. Transparency via shared interactions and lower friction in communication. The agri-food supply chain faces numerous inefficiencies due to the lack of transparency in the supply chain and inconsistencies in data management (Kamble, Gunasekaran, & Sharma, 2020). Empirical evidence from multiple case studies focused on the food industry by Taylor and Fearne (2009) has indicated a disconnection between the food supply chain and consumer demand due to the presence of several intermediaries. The presence of constant intermediaries in the production system increases the risk of misalignment of supply and demand, and demand amplification (the unjustified increase in variability of orders across upstream supply chains due to miscommunication). There is also the problem of a lack of transparency owing to data discrepancies (i.e. different sets of data across the network not matching up), interoperability deficiency (i.e., a failure in real-time exchange and making use of information among system components), and poor data processing (Wang & Yue, 2017). Transparent information processing reduces data discrepancies and leads to better inventory positioning and lower costs throughout the supply chain. Blockchain technology is expected to play a key role in improving the level of transparency and responsiveness in the agricultural supply chain (Bronson & Knezevic, 2016; Carbonell, 2016; Kshetri, 2017).

As indicated in Table 2, transparency in the food supply chain will be improved with increased shared and public interactions (e.g., Guido, Mirabelli, Palermo, & Solina, 2020; Longo, Nicoletti, & Padovano, 2020; Malarvizhi, 2019; Zhang et al., 2021) as well as the reduction of friction in delivering information (e.g., Bumblauskas, Mann, Dugan, & Rittmer, 2020; Syromyatnikov, Geiko, Kuashbay, & Sadikbekova, 2020; Tsolakis, Niedenzu, Simonetto, Dora, & Kumar, 2021). The former refers to the fact that a distributed consensus mechanism increases trust among the network's participants (Chen et al., 2019; Mainelli & Smith, 2015; Walport, 2016) and the latter refers to the smooth flow of information

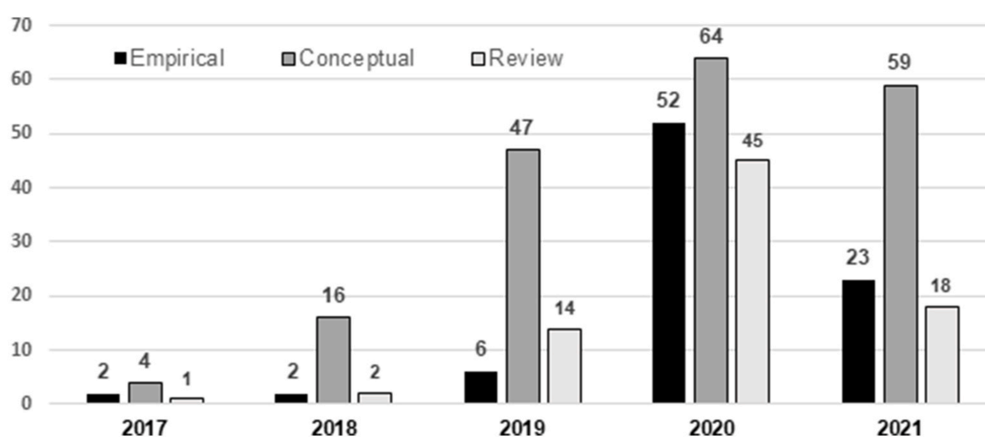

Fig. 3. The number of articles related to the application of blockchain in the agri-food sector, total = 353 (empirical = 83, conceptual = 190 and review = 80), up to August 31, 2020).

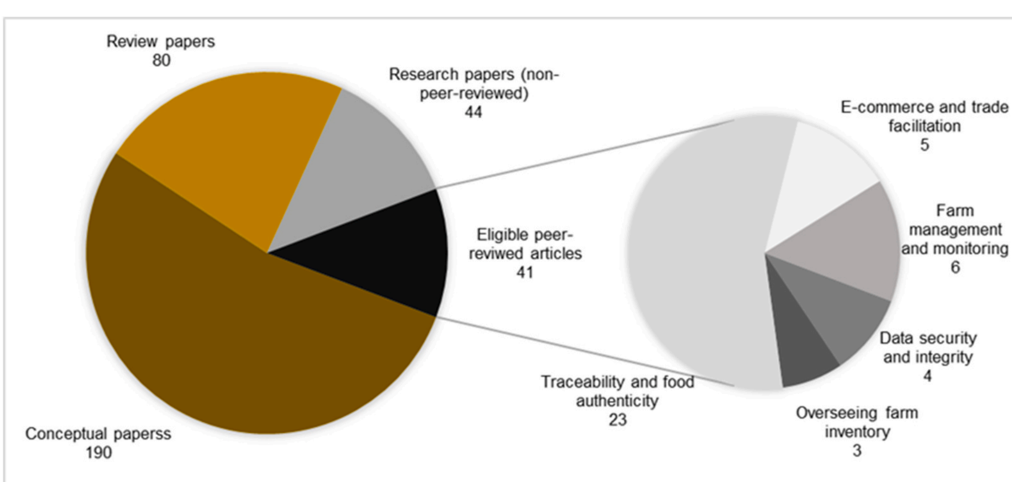

Fig. 4. The distribution of retrieved articles with empirical evidence of blockchain technology implementations in agri-food (a total of 355 articles retrieved, including 190 conceptual papers, 80 review papers, 44 research papers (non-peer-reviewed) and 41 research papers with empirical evidence of agri-food use cases).

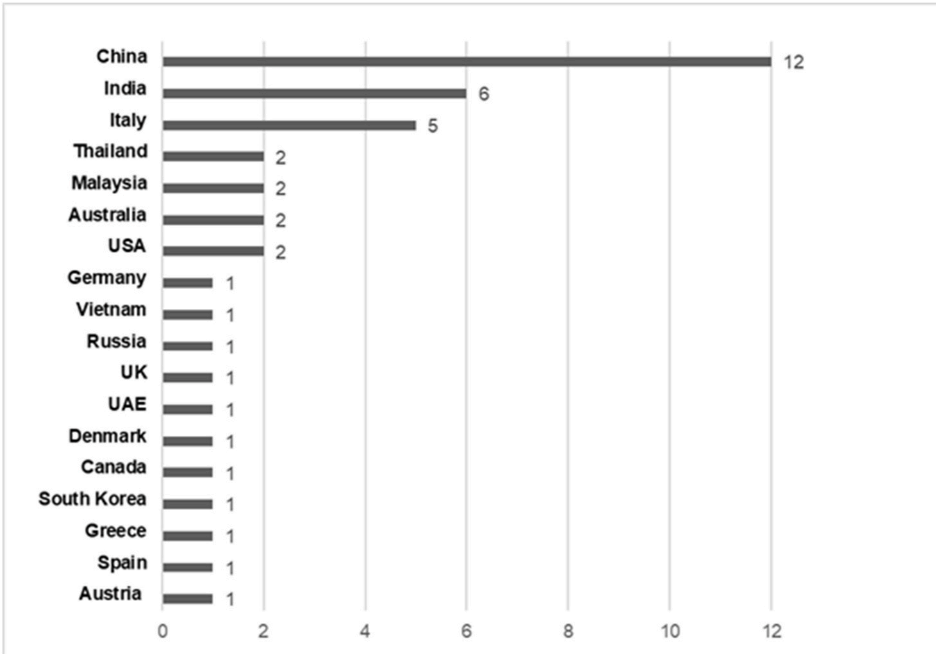

Fig. 5. Distribution of empirical articles across countries (total retrieved articles = 41). Note that in Cao et al., 2021 two countries are reported.

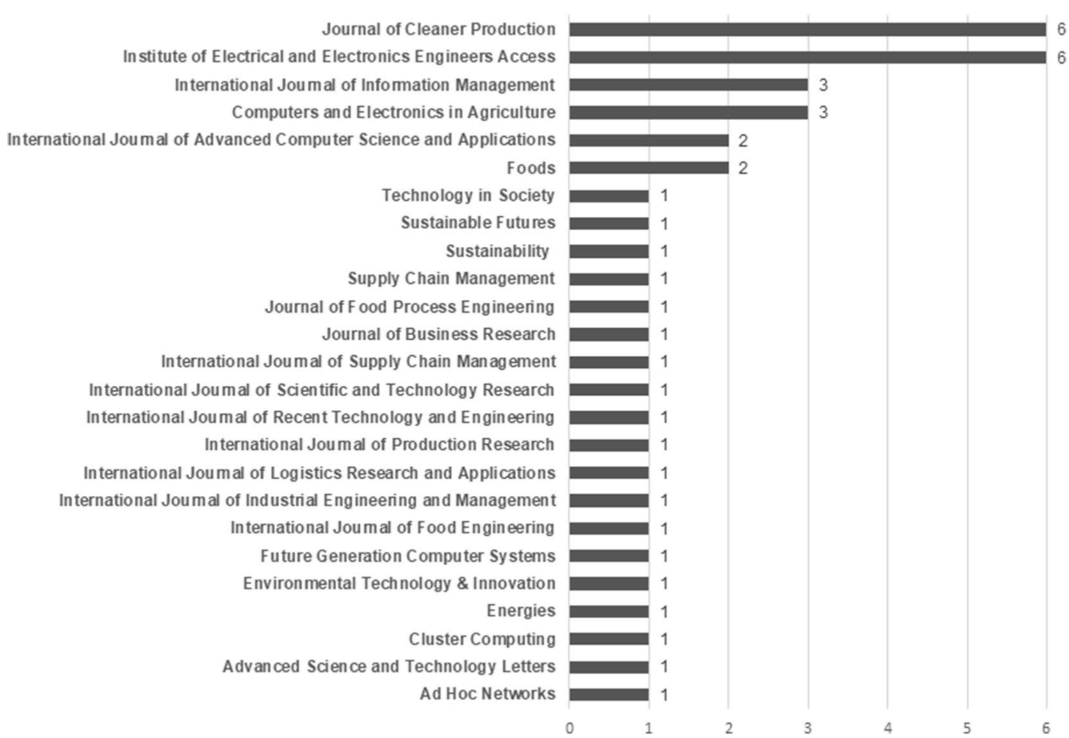

Fig. 6. Published articles on the development of blockchain in the agricultural sector, across journals (total retrieved articles = 41).

and the reduction of the friction that imperfect information creates (English & Nezhadian, 2017; Kim & Laskowski, 2018).

Kamble et al. (2020) pointed to the advantages of blockchain technology in which information is shared and stored in ledgers among participants at each node. Hence, the transactions are accessible and verified at any time in the future without the risk of being lost (Longo et al., 2020). Transparency in network activities and operations delivers high visibility to all the participants, thereby diminishing the need for a trusted intermediary (Abeyratne & Monfared, 2016). Zhang et al. (2021) proposed a blockchain-based system for the traceability of frozen aquatic products. According to Zhang et al. (2021), adopting this system allowed participants to share more reliable tracking information. Due to multiple verification and identification mechanisms, the proposed system prevented unauthorized access or false information. Therefore, this has led to increased consumer confidence in the quality of aquatic food and increased consumer motivation to buy (Liu, Long, Song, & He, 2020; Zhang et al., 2021). By presenting the Ethereum blockchain for monitoring the dairy supply chain, Longo et al. (2020) showed that all

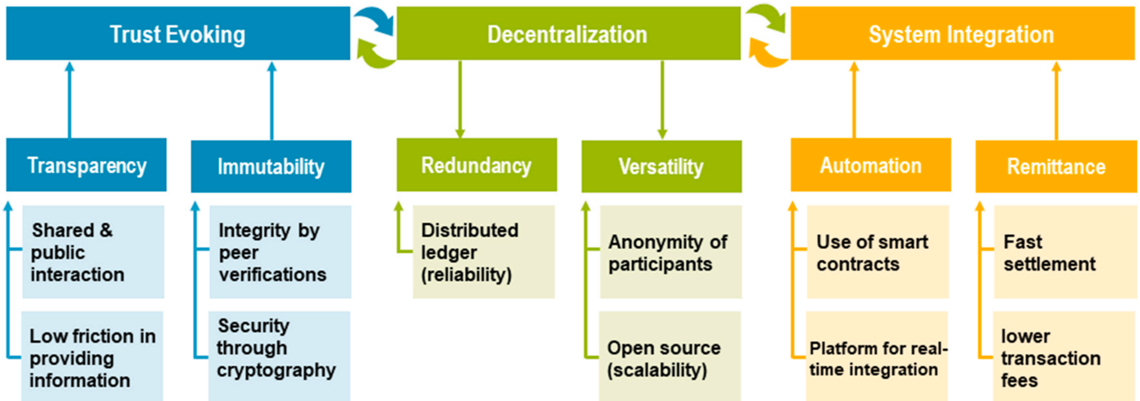

Fig. 7. Characteristics of blockchain technology based on analyses provided in Tables 2–4

information can be shared along the whole network. All transactions were documented and recorded as the history of a product, from its production on the farm to its sale to the consumers. However, the study by Tönnissen and Teuteberg (2020) asserted that successful implementations require a large number of stakeholders in the global logistic chains to participate in the blockchain-based applications and hence not necessarily result in reduced intermediaries.

Moreover, blockchain provides immense potential for low friction in communication, since individuals, organizations, devices, and algorithms can easily interact with each other (Disparte, 2018). The friction of information mostly flows across distant locations involved in the food supply chain. There is a constant need for actors in the agri-food supply chain to collect and verify information, which is particularly crucial for financial transactions (Hamam et al., 2023; Martin, 2000). Literature has pointed to the challenges facing the agricultural financing system due to the low credit status of agricultural businesses (Martin, 2000; Zhang, 2020). For instance, a credit check is a lengthy process and affects transactions. Zhang (2020) studied the application of blockchain in an agricultural financial system and asserted that this technology facilitates smooth information flow through agri-food transmission channels towards financial and insurance institutions. Their study confirmed that blockchain can reduce the time needed for financing the agricultural value chain.

The agri-food system is characterized by imperfect information and asymmetric allocation along the supply chain (e.g., Antle, 2001; Starbird & Amanor-Boadu, 2007). This asymmetry of information eventually leads to increased transaction costs and market failure (Bogetoft & Olesen, 2004). In particular, literature has looked at the lack of information on food safety and quality attributes which are difficult to assess in many cases (see e.g., Hobbs, 2004; Maesano, Di Vita, Chinnici, Gioacchino, & D'Amico, 2021; McCluskey, 2000). Therefore, the information relating to product safety and quality aspects (including ethical or environmental issues) is greatly asymmetrically allocated along the supply chain (Starbird & Amanor-Boadu, 2007). Safety and quality attributes are, in many cases, considered as experience attributes (determined only after consumption e.g., taste and freshness) or credence attributes (that are difficult to ascertain even after being consumed e.g., animal welfare, naturalness) (for review on food attributes refer to Benz, 2007; Grunert, 1997; Nelson, 1974).

Chen, Li, and Li (2020) examined the concept of 'digital agricultural democratization' using an ecological farm case study. They demonstrated that blockchain-based systems can resolve the problem of asymmetric information and unreliable third-party institutions in organic food systems. Bumblauskas et al. (2020) examined the application of blockchain and IoT-enabled technologies in an egg supply distribution system. Bumblauskas et al. (2020) noted that a traceable food supply chain enables consumers to access more data about products and enables them to make more informed food choices. In their system, they used a permissioned blockchain (i.e., a blockchain with a security mechanism in which certain actions are allowed to be performed only by identifiable participants) for managing the recording of data to the ledger and accessing transaction history data. This resulted in reduced information asymmetry and reduced the risk of food recalls across the whole supply chain (Bumblauskas et al., 2020). Liu et al. (2020) pointed to the demand information asymmetry which impedes agricultural development. They studied the effect of adopting blockchain and big data on the estimation of demand for greener (and fresh) agricultural products. They found that the overall benefits for the entire agri-food supply chain would be higher with the application of blockchain-enabled big data. The fusion of blockchain and big data resulted in more consistent, accurate, and reliable information transmitted across actors and increased trust in the safety of food (Bumblauskas et al., 2020 While these studies confirm the role of blockchain in reducing communication friction, Kim and Laskowski (2018) indicated that its implementation in certain agricultural sectors, such as livestock and dairy, faces significant challenges. The complex and fragmented processes and data points in these sectors make it difficult to achieve the same clear-cut benefits observed in crop farming).

3.2.1.2. Immutability through peer verification and cryptography. Numerous recent food incidents (such as the milk scandal in China, and the horsemeat and Salmonella-contaminated egg scandals in Europe) have damaged consumer trust in the food system (for a review refer to Ling & Wahab, 2020). Recurrent food scandals have led to the introduction of a myriad of regulations for more strict governance of the agri-food sector (Marucheck, Greis, Mena, & Cai, 2011). Hence, the issue of the integrity of transactions within the agri-food supply chain became a cornerstone of food authentication (Ling & Wahab, 2020). Traditional information technology systems that are deployed to share information involve certain forms of centralized authority mechanisms to safeguard the integrity of the network. Blockchain technology, however, can ensure the integrity of transactions by creating immutable ledgers. As revealed in Table 2, blockchain-based integrity relates to the peer verification of transactions (e.g., Cao et al., 2021; Chan, Abdullah, & Khan, 2019; Zhang et al., 2021) and cryptography algorithms for security (e.g, Ferdousi, Gruenbacher, & Scoglio, 2020; Violino et al., 2019; Yang et al., 2021). Peer verification of transactions refers to the consensus mechanism used to achieve a unanimous agreement on data values among members of the network (Chen et al., 2019; English & Nezhadian, 2017; Liang, 2020). Cryptography is a rather complex mathematical algorithm that functions like a firewall against tampering (Liang, 2020).

Currently, several modern monitoring and traceability methods have been employed in the agri-food sector (Barge et al., 2020). For instance, sensors, RFID (Radio-Frequency Identification) and biometric identifiers are used for tracing cattle from farm to slaughter (Shanahan et al., 2009), or tracking the movement of beef across the supply chain to ensure regulatory compliance (George, Harsh, Ray, & Babu, 2019). However, these methods are subject to limitations in verification processes, calling for a need for a traceability mechanism with the capacity to exchange trustworthy information between actors in the food chain (Behnke & Janssen, 2020). Peer verification of transactions can be gained in the blockchain system using a consensus algorithm to achieve agreement on the state of the network (Liang, 2020; Zhao et al., 2019). Examples include peer verification mechanisms in the beef industry (e.g., Cao et al., 2021; Ferdousi et al., 2020) and for aquatic products (e.g., Zhang et al., 2021).

Using blockchain-based 'human-machine reconcile mechanisms' (i.e., a combination of human and machine capabilities), Cao et al. (2021) proposed a framework with shared traceable responsibilities across beef supply chain actors. Meat products need to be properly transported and stored (i.e., chilled, or frozen) to avoid spoilage. Therefore, it is important to monitor both the exchanges of products across supply chain actors (i.e., production information such as quantity and feeding method) and the state of the meat products (such as the humidity and temperature) during transit (Cao et al., 2021; Hintze, 2019). Data about the animal breed and types of feed (e.g., grass-fed or grain-fed) is reconciled and verified through the multi-sig validation protocol (in which transaction execution requires two or more signatures) across the network to ensure shared responsibilities. According to Cao et al. (2021), data tampering can be prevented by updating real-time information (using wireless RFID sensors and IoT equipment) about product details (e.g., temperature, humidity, storage time, traded quantity) in both the product's profile and its tag.

Leng, Bi, Jing, Fu, and Van Nieuwenhuyse (2018) pointed out that the agricultural supply chain in China is characterized by having a large number of scattered small and medium-sized enterprises with limited access to commercial resources. In particular, the agricultural business resource coverage rate in remote areas is extremely low, and enterprises can hardly meet the demands for agricultural products. Leng et al. (2018) investigated the potential of blockchain technology to overcome the current challenge of limited commercial resource access. They proposed dual-chain agricultural business resource public blockchain architecture integrating a decentralized resource mechanism and making on-demand scheduling. It is designed based on a 'user information chain' to record and store user information (i.e., agricultural business enterprises) as well as a 'transaction chain' to record and store all transaction data on the public service platform. They concluded that the dual-chain model provided adaptive rent-seeking and matching structures for public service platforms. The system ensures the transparency and security of transaction information as well as maintaining the privacy of enterprise information (Leng et al., 2018). In another study, Rogerson and Parry (2020) investigated the impact of blockchain technology on the food supply chain through case studies. The findings from the cases demonstrated how blockchain (most likely) increases visibility and trust as a result of the decentralized, consensus-based mechanism underpinning the technology (Rogerson & Parry, 2020). It also reduces the risk of human error and counterfeit goods. However, the authors asserted that, in practice, the development of blockchain-based solutions with full visibility can be costly.

Integrity in the food supply chain can also be enhanced through blockchain's cryptography and hash verification mechanism (Kamble et al., 2020). The importance of enhanced security through cryptography has been substantiated in a large number of reviewed blockchain-based traceability systems (e.g., Cao et al., 2021; Chen et al., 2020; Ferdousi et al., 2020; Yang et al., 2021; Zhang, Han, et al., 2020; Zhang, Sun, et al., 2020). In a case study of the designing of a traceability blockchain-based system for fruits and vegetables, Yang et al. (2021) used cryptographic algorithms, such as signature verification and hashing, to ensure tamper-proof modification, anti-counterfeiting, and non-repudiation (i.e., information delivery proof from both sender and receiver) in the process of data transmission. Ferdousi et al. (2020) proposed a blockchain supply chain framework for the beef cattle industry. The suggested framework led to faster verification of transaction data without the need to request data from independent local databases. Each farm in this model stores animal-related data locally on its premises. A local database would contain tables of data in which, once the tables are updated, a cryptographic hash is generated. This procedure prevents data from being altered by a single owner without renewing the hash algorithms in the blockchain network. When the transaction was performed and the animals were transferred, the animal data was sent to the new owner. The new owner could check the hashes of the animals stored in a smart contract (called a FarmManager contract) and match the data by recalculating the hashes from the received data. However, as underscored by Kamble et al. (2020), although blockchain technology holds promise for enhancing data integrity in the agriculture supply chain, its effectiveness is hampered by the significant implementation costs and the shortage of technical expertise among stakeholders.

3.2.2. *The importance of decentralization*

The current centralized agricultural supply chains are vulnerable to third-party tampering, with issues around the confidentiality of information or the privacy of network actors (Bischoff & Seuring, 2021). In addition, farmers are concerned about irregularities and middleman payment fraud (Pooja & Mundada, 2020). Decentralization in blockchain technology allows for the shifting of system governance from a centralized entity to a distributed network. As depicted in Table 3, two important features that contribute to blockchain decentralization are redundancy and versatility.

3.2.2.1. Data redundancy by distributed ledgers. The importance of a blockchain's decentralized features has been addressed in the majority of reviewed articles (e.g., Ferdousi et al., 2020; Kumar & Iyengar, 2017; Li et al., 2020; Zhang et al., 2021). Li et al. (2020) for instance, compared blockchain-based e-commerce with the traditional electronic-agriculture system in the Australian aquaculture industry. Li et al. (2020) concluded that decentralized blockchain-based e-commerce provides greater advantages to farmers in comparison with traditional e-commerce for establishing trustworthy provenance. They found that blockchain, in this context, serves as a foundation for creating a distributed ledger of transactions. This ledger is not centralized but is distributed across the network, ensuring that each participant in the blockchain holds a copy of the entire transaction history. Therefore, this will fundamentally enhance trust and security among individuals, the interaction between humans and machines, and transactions involving machine-to-machine operations. This is particularly relevant for farmers engaging in e-commerce transactions, as trust is crucial in their interactions with buyers, suppliers, and other stakeholders. However, the results of other studies conducted by Garrard and Fielke (2020) and Köhler and Pizzol (2020), challenged the advantage of using blockchain-based ledgers. Garrard and Fielke (2020) investigated the potential of a blockchain ledger to enable product tracking in the prawn aquaculture industry. The authors did not find a significant advantage to using a blockchain-based ledger in product tracking, although it helped to digitize the operations. They pointed out that blockchain is a relatively new technology whose applications are still under development. Over time, more solutions may be discovered that significantly increase the value of a blockchain ledger compared to a traditional database. However, it is important to recognize that there is considerable hype around blockchain and that some of the proposed applications may not be practical. Köhler and Pizzol (2020) analyzed six cases of blockchain-based systems implemented in different food supply chains (including tuna, coffee, and egg products). They assessed the components of the blockchain-based cases (such as decentralized platforms, devices, the knowledge required for stakeholders, and management processes) and concluded that decentralization of information and immutability mechanisms increase transparency, traceability, and trust.

However, no strong evidence exists regarding other possible advantages, such as increased sustainability and improved data management. They noted that these advantages are not directly attributable to the blockchain itself as they can also be acquired by employing non-blockchain-based platforms (Köhler & Pizzol, 2020).

3.2.2.2. Versatility acquired from anonymity and open-source initiative. From reviewing the literature, we can infer that the anonymity of participants (e.g., Ferdousi et al., 2020; Viriyasitavat & Hoonsopon, 2019) and the open-source nature of the technology (e.g., Cao et al., 2021; Violino et al., 2020; Yang et al., 2021) made the blockchain a versatile technology (see Table 3). The food industry is under pressure from consumers to divulge more transparent information about their production process, sustainability, and animal welfare practices (Božić, 2017). In an effort to add more transparency to the agri-food chain, EU Regulations (EU 2019/1381) came into effect which provided greater transparency and sustainability of risk assessment in the food chain. However, protecting confidential information while being transparent with supply chain information is increasingly becoming a major concern. In such cases, permission blockchain systems are considered more appropriate than public blockchains. As an example, Ferdousi et al. (2020) argued that the US beef industry lacks sufficient traceability, as most cattle owners regard such information as confidential. Ferdousi et al. (2020) proposed a cattle supply chain traceability framework using a permissioned blockchain network. This framework maintains users' anonymity to protect identities and allows users to store their data locally while ensuring that changes to transactions are securely recorded in the chain through cryptographic hashes. This framework enabled the owners to access the aggregated data at any time and decide how long the data should be stored or whether it should be shared with other farm owners.

The open-source feature of blockchain technology makes it scalable to various commercial platforms. Open-source blockchains are collaboratively created (by unaffiliated developers), distributed without restrictions, published transparently, and developed as a public good rather than the property of a business entity (Raymond, 1999). Open-source blockchain frameworks (such as Hyperledger, Enterprise Ethereum, Corda, etc.) allow developers to construct decentralized functions that provide solutions for various agri-food supply chain problems. The information management system developed by Yang et al. (2021) exemplifies open-source blockchain traceability for the agricultural supply chain. The model used the Hyperledger Caliper performance evaluation mechanism, an open-source blockchain, which enables users to carry out network performance tests through predefined use case indicators (Yang et al., 2021). The system performance is configured over transaction latency and transaction throughput over numerous send rates. Transaction latency refers to the time elapsed between a transaction recorded on a network and the first confirmation by the network. Transaction throughput is the rate at which valid transactions are committed across the entire blockchain network within a specified period. The model also included a reputation-based smart contract (using an incentive mechanism) to ensure peers' participation in sharing data.

3.2.3. System integration and efficiency

As depicted in Table 4, reviewing the literature suggests that trust-evoking mechanisms (such as transparency and integrity) and decentralized features (including redundancy and versatility) pave the way for system integration through automation (e.g., using smart contracts and IoT real-time synchronization) and improved remittance (e.g., reducing the transaction time and costs).

3.2.3.1. Automation through integration with IoT and smart contracts. The increasing population and demand for food pose significant challenges to the agri-food system, necessitating advancements in technology to enhance productivity and efficiency. Automation and Internet of Things (IoT) applications are crucial in addressing these challenges by enabling better monitoring, management, and optimization of agricultural processes (Jha, Doshi, Patel, & Shah, 2019). However, the rapid adoption of automation and IoT technologies also brings concerns such as data security (Alonso, Sittón-Candanedo, García, Prieto, & Rodríguez-González, 2020; Zhang et al., 2021) and efficient real-time data collection and processing (Chen et al., 2020; Jha et al., 2019; Yang et al., 2021). Blockchain allows data to be accessible to multiple actors concurrently and its automation features can solve such issues. Blockchain provides a platform for automation in the agricultural sector, acting as the bridge between digital and traditional agri-food production (Lin et al., 2017). Blockchain frameworks facilitate the use of smart contracts, to connect food supply chain stakeholders promptly, reducing the cost and interruptions caused by intermediaries when authenticating traditional contracts (Kamble et al., 2020; Mao, Hao, Wang, & Li, 2018; Tan, Gligor, & Ngah, 2020). Furthermore, it allows for cryptocurrencies and micro-payments (e-commerce for very small financial transactions that the traditional financial system cannot handle) that support IoT devices and enable machines to interact autonomously (Reyna, Martín, Chen, Soler, & Díaz, 2018).

Examining the literature shows how smart contracts are the cornerstone of agri-food blockchain applications (e.g., Casino et al., 2021; Ferdousi et al., 2020; Zhang et al., 2021). Smart contracts allow computations inside the blockchains (Salah, Nizamuddin, Jayaraman, & Omar, 2019; Zhang et al., 2021), therefore operating as a decentralized virtual system (Casino et al., 2021; Dolgui et al., 2020). Commonly, smart contracts are protocols or programs that satisfy contractual requirements, such as payment terms, confidentiality, and execution of activities, by reducing the need for trusted intermediaries (Buterin, 2014; Van Wassenaer et al., 2021). This allows the automatic execution or enforcement of an operation if certain predefined conditions are met (Dolgui et al., 2020). More concretely, traceability automation is provided by the real-time data synchronization and self-executing capabilities of smart contracts. For example, Casino et al. (2021) designed a traceability system for dairy products using smart contracts and a local private blockchain. The essential interactions concerning products, processes, and stakeholders were executed using smart contracts. Salah et al. (2019) proposed a blockchain-based traceability method for soybean transactions throughout the food supply chain. The suggested method used the Ethereum blockchain and smart contract on top of the InterPlanetary File System (IPFS). The IPFS is a peer-to-peer network protocol to store and share traceable data in a distributed file system to reduce the volume of data stored on the chain (Yang et al., 2021). The proposed model builds on the utilization of smart contracts to govern interactions and transactions across the supply chain ecosystem. Transactions are stored in an immutable ledger with tracing links to an IPFS decentralized file system; this enhances the transparency, reliability, and efficiency of soybean business transactions (Salah et al., 2019).

Depending on the level of use and underlying programming languages, different forms of smart contracts exist (Atzei, Bartoletti, & Cimoli, 2017; Varela-Vaca & Quintero, 2021). For instance, Zhang, Sun, et al. (2020) developed a blockchain-driven information management system for the grain supply chain, in which the information management mechanism is realized through two types of smart contracts: custom and expanded smart contracts. A custom smart contract executes different functions according to relevant predefined indicators. When information is transmitted to the node, the relevant smart contract will process it, triggering related functions if the preset conditions are met. The expanded smart contracts deal with the specific requirements of different enterprises involved in the network (Zhang, Sun, et al., 2020). In another example, Yang et al. (2021) designed blockchain-based traceability for the storage and querying of information in the agricultural products (fruit and vegetable) supply chain. The model included a reputation-based smart contract (i.e., using an incentive mechanism) that improved the efficiency and security of private information, as well as ensuring the reliability of data. When the data is uploaded to the system at each node, it triggers the smart contract logic to execute the corresponding operation if it meets specified requirements. However, with a reputation mechanism, each node will be rewarded to ensure peer participation and therefore the integrity of the shared traceability data between upstream and downstream links.

In addition to the automatic operations executed with smart contracts, blockchain technology provides a platform for integrating IoT solutions (e.g., Casino et al., 2021; Feng, Wang, Chen, & Zhang, 2020; Iqbal & Butt, 2020; Nesarani, Ramar, & Pandian, 2020). IoT solutions (including Wireless Sensor Networks, Radio Frequency Identification (RFID), and drones) are being deployed in different agri-food sectors, optimizing production and fostering smart farming (Díaz, Martín, & Rubio, 2016; Grecuccio, Giusto, Fiori, & Rebaudengo, 2020). IoT solutions generate and transmit large volumes of data and demand consistent connectivity (Reyna et al., 2018). This, combined with issues such as limited memory processing capacity, failures in network connectivity, and power supply requirements, pose various challenges (Reyna et al., 2018). For example, Iqbal and Butt (2020) developed an IoT-based farm monitoring system to protect crops from animal attacks during all stages of a harvest. The system detects the presence of an animal using the sensor nodes deployed in the field and sends signals to a Repelling and Notifying System (RNS) in the field. Then, the RNS generates human-safe ultrasonic sound pulses (which are unbearable for animals), which keep the animal away from the farm. The RNS system also records the hazard incidents in a centralized Farm Management System (FMS) maintained by the farmer. Indeed, each FMS can be considered to be a blockchain node that provides a shared ledger of the details of incidents in connection with metadata reported by other nodes in the blockchain. The proposed safe farming system creates consensus between farmers, regulators, and distributors about incidents across the farmed area, enabling them to make immediate, effective decisions.

Tsolakis et al. (2021) pointed to the lack of database integrity between the fish supply chain and Thai authorities. This lack of integrity instigates data inaccuracy issues, such as an improper number of registered vessels, thus overlooking illegal fishing and impeding traceability in the fish industry. They studied the design of blockchain-centric food supply chains that promote sustainable development goals in the context of the Thai fish industry. The findings indicated that the use of sensors and automation (e.g., RFID e-tagging and scanning of fish) integrates total quality management in the blockchain. RFID tags store critical data transmitted directly from sensors (e.g., locations, vessel data, date, time, temperature) which eliminates human errors and intentional fraud. In addition, the smart weighing system (weighing the logging of the fish caught taking into account the vessel's movement throughout fishing operations) helps transmit automated estimation of the landing date to the selected port and thus increase operational efficiency. Moreover, onboard cameras and electronic monitoring systems help to identify by-catches and protected fish species and make appropriate decisions (Tsolakis et al., 2021).

3.2.3.2. Remittance with fast settlement and lower fees. Trade finance plays a crucial role in providing services such as credit, insurance and guarantees in global agri-food trade. The existing systems of trade finance are complex, time-consuming, and heavily paper-reliant when performing transactions (Tripoli & Schmidhuber, 2018; Zarbà et al., 2023). Transactions consist of agreements on trade terms, but these terms mostly pose a counterparty credit risk to growers. Furthermore, the transactions include financial intermediaries which can delay the transaction as they process the contracts (Tripoli & Schmidhuber, 2018). Distributed ledger trade platforms reduce the risk and cost of transactions. Workflow automation and digital ledger documentation (e.g., agreements and certifications) bring a high degree of traceability and verifiability and, hence, improve transaction efficiency (Rühmann, Konda, Horrocks, & Taka, 2020). Smart contracts enable blockchain trade platforms to auto-execute the settlement of payments instantaneously, through valuing the commodity, validating the buyer's funds, and securing the reserved funds for the pending delivery (Tripoli & Schmidhuber, 2018). Once the commodity is delivered, the ownership is transferred to the buyer as the real-time payment is settled from the retained funds (Tripoli & Schmidhuber, 2018).

As presented in Table 4, blockchain-based systems are being employed in different agri-food areas to improve trade efficiency through faster transactions (e.g., see Ferdousi et al., 2020) or reduced transaction costs (e.g., Morya, Amoah, & Snaebjornsson, 2020; Tan & Ngan, 2020). For instance, Louis Dreyfus Co (LDC), one of the leading commodity trading companies, together with Dutch and French financial institutions, is developing and testing a blockchain-based platform to digitize the entire trading cycle (Kamilaris et al., 2019). They have conducted a pilot test on soybean shipments between the U.S. and China using a blockchain-based platform. The results indicated that by automatically matching data in real-time, circumventing manual controls and duplication, document processing (e.g., letter of credit and sales contract) is reduced. In a traceability model for beef cattle, Ferdousi et al. (2020) employed the Proof of Authority (PoA) consensus mechanism which improved transaction settlement by eliminating expensive hash computations. Tönnissen and Teuteberg (2020), using multiple use cases (e.g., Agri-Digital, Animal Product, and Origin Tracking), analyzed the impact of blockchain technology on operations and supply chain management. One of the use cases they analyzed was 'Agri-Digital', an application that uses cryptocurrency payment for commodity transactions. The authors argue that AgriDigital provides fast settlement and traceability verification in the grain supply chain. The application provides secure transactions and a fast payment process using cryptocurrency (called "Agricoin") enforced by smart contracts. As another recent example, Tan and Ngan (2020) found that the fusion of smart contracts and IoT in supply chain management counter both adulterations/contaminations and counterfeited dairy products. They also found that the blockchain framework increased dairy supply chain effectiveness in terms of operations, costs, time, and human resources. Moreover, statistical analysis by Li et al. (2020) has indicated that blockchain e-commerce provides great convenience to farmers, increasing trade by 25% on average compared to traditional e-agriculture, and accelerating the development of sustainable smart agriculture.

4. Discussion

Understanding the enabling characteristics of blockchain technology is essential to its effective implementation in the agri-food domain. The present review delivers an extensive overview of the relevant characteristics of blockchain agri-food applications. Our review identified two major themes across the articles reviewed: a) the great potential for agri-food applications, particularly in food traceability and authentication and b) immutability, decentralization, and automation as the main enabling features in the agri-food sector, with, however, some challenges to overcome. Our critical evaluations also reveal mixed results in the application of blockchain in agri-food supply chain management, with a few cases showing limited impact. This highlights the multifaceted nature of the technology and its varied outcomes. The following sections first discuss the identified themes, then discuss reasons for observed disparities in blockchain effectiveness, and finally outline directions for future research.

4.1. The potential of blockchain implementation in the agri-food sector

There is a wealth of literature on the application of blockchain in agri-food systems (Ganne, 2018; Kamilaris et al., 2019; Martinez et al., 2019), largely of an exploratory nature (Van Wassenaer et al., 2021) and still at the theoretical level (Chen, 2018; Dona, 2019; Hartmann & Thomas, 2020). Our review showed that the main blockchain use cases in the agricultural sector include farm management and monitoring, e-commerce, overseeing farm inventory, and traceability. Across this range, blockchain characteristics have the best fit for traceability. The ability to instantly trace the entire lifecycle of food products from the farm through every point of the supply chain to the consumer strengthens integrity, efficiency, and safety. This finding corroborates those of Pandey et al. (2022), Xiong et al. (2020) and Harshitha, Shashidhar, and Roopa (2021), which state that blockchain's characteristics of transparency, security and decentralization enable efficient food traceability. This facilitates reducing food fraud and tampering with transaction data within the food supply chain (Xiong et al., 2020). However, the storage security of monitoring data is still a challenge (da Silveira et al., 2021; Wang & Wang, 2017; Zhao et al., 2019). Solutions that have been proposed include a double-chain storage mechanism in which the chain data structure is utilized to store the blockchain transaction hashes, with another chain storage designed in parallel to prevent malicious and illegal tampering of the agricultural product data (e.g., Li et al., 2020). However, more research is needed to verify the efficiency of such mechanisms for wider blockchain solutions.

Among other uses, blockchain has the potential to improve agricultural e-commerce and farm management. A lack of transaction integrity has become a major problem limiting the rapid development of e-commerce (Dey & Shekhawat, 2021; Furfaro, Argento, Parise, & Piccolo, 2017). Blockchain has the potential to improve the integrity of transactions, though even with blockchain technology, integrity still lies in the hands of individuals in the network to some extent. Currently, the agri-food sector suffers from a lack of a unified system with definitive principles to regulate these transactions (Li et al., 2020). In addition, farmers' lack of technical knowledge and limited budgets are the major barriers to the adoption of blockchain-based systems for farm management and electronic agriculture. Farmers' lack of sufficient funds will bring serious challenges to developing a blockchain-based e-commerce system for the production and promotion of their locally produced agricultural products on a large scale (Arias, Wurm, Hoang, & Jin, 2015).

4.2. Enabling characteristics of blockchain in agri-food applications

Our review identified the main blockchain enablers for agri-food implementations as: *a)* a trust facilitating mechanism that creates transparency (e.g., shared & public interaction, lower friction in providing the information) and immutability (e.g., peer verifications, using cryptography) as part of the architecture of the technology, *b)* system decentralization through features of redundancy (i.e., distributed ledger) and versatility (e.g., the anonymity of participants and open-source capabilities), and *c)* system integration from automation (e.g., use of smart contracts, integration with IoT) and remittance (e.g., fast settlement, lower transaction fees) features. This has been corroborated by the findings of Kamble et al. (2020) which examined expert opinions on blockchain features and found that immutability and distributed ledgers are the most important enablers of blockchain implementations in the agri-food domain.

There is ample evidence that blockchain has great relevance to the agri-food industry since the transactions in this sector are burdened with trust problems and asymmetry in information communication (see e.g., Sylvester, 2019; Tripoli & Schmidhuber, 2018). Lack of transparency has always been one of the challenges of the supply chain due to data inconsistencies (Wang, Han, & Beynon-Davies, 2019). Shankar, Gupta, and Pathak (2018) mentioned this as a key factor in organizing supply chain logistics. As discussed earlier, creating a specific copy of the network in each node and inspecting the data blockchain creates transparency in the network, which reduces the need for a reliable intermediary due to greater visibility for all stakeholders (Abeyratne & Monfared, 2016). However, this effect is context-dependent and does not necessarily result in reduced intermediaries since successful implementations still require a large number of stakeholders in the global logistic chains to participate and use the blockchain-based applications (Tönnissen & Teuteberg, 2020).

The decentralization feature allows blockchain-based solutions to be non-reliant on central authority (Köhler & Pizzol, 2020; Liu et al., 2020; Zarrin, Wen Phang, Babu Saheer, & Zarrin, 2021). However, to be effectively implemented, blockchain needs to be connected to existing legacy systems and databases, such as management systems, warehousing software, and enterprise resource planning platforms (Xiong et al., 2020). Therefore, middleware and communication protocols play a key role in connecting these existing legacy systems to blockchain architectures. Developing such infrastructures is often time-intensive and costly (Kim & Laskowski, 2018).

Our review also indicated that among blockchain features, the roles of integrity and automation are particularly prominent. Agriculture and food production are increasingly approaching an era in which traditional agricultural production is shifting towards more automated and technology-driven production systems. As discussed by Köhler and Pizzol (2020), blockchain technology is not a stand-alone platform and would be a blank ledger without the use of other technologies. Indeed, smart agriculture requires the execution of smart contracts and integration with other IoT devices. It is widely acknowledged that smart contracts enable blockchain systems to streamline business transactions and the audit trail of certification (Van Wassenaer et al., 2021). It can also improve transparency and reduce the cost of interactions by establishing legal restraints among the members of the blockchain network (Van Wassenaer et al., 2021). Yet, in their present state, smart contracts still full legal recognition and enforceability (Christidis & Devetsikiotis, 2016; Drummer & Neumann, 2020; Torky and Hassanein, 2020; Van Wassenaer et al., 2021). Theoretically, smart contracts can serve as legally binding agreements when the identities of the involved parties can be verified (for discussions on the legal status and implications of smart contracts, see Drummer & Neumann, 2020), however, complications arise in situations where participants cannot be identified, as is often the case in many public blockchains.

4.3. Disparities in blockchain effectiveness

While overwhelming evidence suggests that blockchain has the potential to enhance agri-food supply chain management, our analysis has revealed instances where the impact of blockchain was limited or did not meet expectations (see e.g., Garrard & Fielke, 2020; Kamble et al., 2020; Köhler & Pizzol, 2020; Tönnissen & Teuteberg, 2020). The mixed results observed in our review can be attributed to several factors, reflecting the complexity and variability inherent in both the technology itself and the diverse agri-food environments in which it is implemented (Pournader, Shi, Seuring, & Koh, 2020). Blockchain technology is still relatively new, and its applications are continuously evolving. Some studies may reflect early-stage implementations where challenges such as high initial costs, lack of technical expertise, and resistance to change can impede successful outcomes (Kamble et al., 2020; Kamble, Gunasekaran, & Arha, 2019). Conversely, studies reporting positive impacts might be documenting more mature implementations where initial challenges have been addressed, and the technology has been fine-tuned to meet specific needs (Kshetri, 2018; Lei, Xu, Liu, Liu, & Sun, 2022). Additionally, the scalability and integration capabilities of blockchain solutions can vary due to legal and technical infrastructures (Lei et al., 2022; van Hoek, 2019), influencing their effectiveness across different studies (Treiblmaier, 2018). In regions with strong regulatory frameworks supporting transparency and traceability, blockchain solutions may thrive and demonstrate clear benefits (Queiroz & Wamba, 2019).

Moreover, the disparity in results can often be attributed to the heterogeneity of the agri-food sector. Different segments within this sector, such as crop farming, livestock, dairy, and fisheries, have unique characteristics, technical requirements and operational challenges. Blockchain technology, while versatile, may offer varying degrees of effectiveness depending on these specific contexts. For instance, in crop farming, blockchain can streamline supply chain traceability and reduce fraud, leading to positive outcomes (Tian, 2017). However, in livestock or dairy sectors, where processes and data points are more complex and fragmented, blockchain implementation might face greater hurdles, resulting in less clear-cut benefits (Kim & Laskowski, 2018). In another example, as highlighted by Garrard and Fielke (2020), the lack of significant advantage in using a blockchain-based ledger for product tracking in the prawn industry suggests that the technology may not yet be mature enough to deliver the expected benefits uniformly across all contexts. Similarly, a recent review by Chiaraluce et al. (2024) on blockchain applications in the wine supply chain highlighted certain challenges. For instance, the review noted that the unique characteristics of the wine supply chain, such as sourcing grapes from various producers, may pose difficulties in the successful utilization of blockchain-based systems.

It is important to note that many current blockchain implementations in the agri-food sector remain at the proof-of-concept level, and research in this area is still evolving (Demestichas et al., 2020). This nascent stage is characterized by pilot projects and theoretical explorations rather than widespread, practical applications (Kamilaris et al., 2019). Recent reviews by Pournader et al. (2020) and Dasaklis, Voutsinas, Tsoulfas, and Casino (2022) underscore that despite the theoretical benefits of blockchain for improving transparency and traceability in supply chains, empirical evidence supporting these benefits in the agri-food sector is still limited and inconclusive. Similarly, the research by Lei et al. (2022) indicated that while blockchain has potential benefits for food safety regulation, its actual impact was not fully confirmed due to technological hurdles and resistance from traditional industry actors This gap between theory and practice highlights the need for more extensive real-world studies to validate the potential advantages of blockchain technology in this field (Dasaklis et al., 2022). As the technology matures and more data becomes available, future research will likely provide clearer insights into its practical applications and effectiveness.

4.4. Future research directions

Blockchain technology is still in its infancy stage and its development needs to overcome challenges such as energy consumption, interoperability (i.e. communicating different blockchain-based systems), scalability, and legal issues (Bermeo-Almeida et al., 2018; Torky & Hassanein, 2020; Tripoli & Schmidhuber, 2018; Yadav & Singh, 2019; Zhao et al., 2019). This review identifies that issues such as energy consumption and scalability are among the most pressing challenges for the food supply chain that require research attention. These results corroborate the findings of Lei et al. (2022) and Demestichas et al. (2020).

Our findings indicate that transparency and immutability are among the enabling characteristics of blockchain technology that determine the architecture of the technology. Immutability to a great extent is influenced by the type of consensus mechanisms employed that determine the validity of transactions and enable cryptocurrencies to function (Ferdousi et al., 2020; Yang et al., 2021). However, the energy consumption of blockchain technology is a complex issue that the success or failure of blockchain implementations. Consensus protocols dictate the energy usage pattern of a blockchain system (Van Wassenaer et al., 2021), which has raised environmental concerns and is the subject of intense research (Krause & Tolaymat, 2018; Sedlmeir, Buhl, Fridgen, & Keller, 2020; Maesano, Milani, Nicolosi, D'Amico, & Chinnici, 2022; Stoll, Klaaβen, & Gallersdörfer, 2019); though blockchain architectures are far from homogeneous and energy consumption patterns per transaction vary greatly amongst blockchain systems (Sedlmeir et al., 2020). There have been discussions on the differences between the energy consumption of various consensus algorithms, such as Proof of Work (PoW) and Proof of Stake (PoS). There is also discussion around emerging alternative distributed ledger technologies gaining momentum, such as Hashgraph, with lower computational energy consumption (Van Wassenaer et al., 2021). Future research on the consensus mechanisms must consider the challenges of international agri-food logistic chains with a wider range of stakeholders across dispersed geographical regions (Pakseresht, Ahmadi Kaliji, & Xhakollari, 2022).

The maturity of blockchain technology and related infrastructure can influence the success of implementations. Early-stage technologies may face scalability, performance, and usability limitations that impact their effectiveness in real-world applications. Scalability is a main concern particularly considering the challenges in integration with different legacy systems (Yadav & Singh, 2019). Transmitting such a massive amount of information across the chain and most likely in the near future with other blockchains (i.e. interoperability) uses substantial network resources alongside increasing propagation delay. This also implies the requirement of storing a large volume of data on the chain and increasing the time required (also known as throughput) for transaction validation. Therefore, scaling blockchain to serve a multitude of different heterogeneous devices across scattered actors is a big technical challenge (Torky & Hassanein, 2020).

5. Conclusion

The number of blockchain-based solutions has been rapidly rising in agriculture and the food industry, though this is mainly at the proof-of-concept level. Technical features that support the application of blockchain in agri-food systems are 1) increased transparency through public interactions and low friction of information, which permits audit trails of certification and transactions, 2) cryptography and consensus mechanisms to ensure the immutability of records, 3) redundancy of records and the open-source nature of blockchain to ensure decentralization, and 4) smart contracts and real-time integration with IoT devices to enable automatic transactions. Presently, the major agri-food application for blockchain is traceability (e.g., provenance) and quality assurance. Food systems are getting increasingly more fragmented, with intricated regulatory compliance requirements. This complexity makes the detection and monitoring of product information and processes along with dispersed networks extremely difficult. It is commonly understood that blockchain has great potential to improve transparency and accountability in agri-food chains. However, for the technology to achieve its full potential – of disruptively transforming food traceability – it should be linked with supportive policies and macroprudential regulatory configurations to ensure financial stability. Moreover, the varying degrees of technological readiness, economic considerations, and stakeholder engagement across different regions and sectors further complicate the implementation and assessment of blockchain technologies.

Moreover, the application of blockchain in the agri-food sector is not without controversies. For instance, there have been concerns regarding greenhouse gas emissions and the environmental impacts of digitization and computational-based solutions. These concerns highlight the need for extensive research and informed discussion to address the technical challenges and environmental impact of blockchain technology. Going forward, harmonious integration of blockchain with regulatory support and a commitment to mitigating environmental impacts will be critical for the technology to reach its peak in revolutionizing food traceability.

While this systematic review pinpointed the characteristics of blockchain that facilitate its integration into the agri-food sector and assess the effectiveness of these features, certain limitations should be acknowledged. The study exclusively concentrates on empirical use cases. Consequently, the scope of this review does not encompass a comprehensive analysis of the entirety of blockchain technology. This focused approach may omit potential insights into broader technical considerations and theoretical advancements that could impact the understanding of blockchain's applicability in the agri-food industry.

Despite these limitations, the study aims to consolidate existing knowledge and present a valuable contribution to the field by emphasizing specific features that support blockchain's applicability in the agri-food industry. The results provide a foundation for future research endeavours, guiding efforts towards the implementation of blockchain-based solutions in the agri-food sector.

CRediT authorship contribution statement

Ashkan Pakseresht: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sina Ahmadi Kaliji:** Writing – review & editing, Resources, Project administration, Methodology, Formal analysis, Data curation. **Karin Hakelius:** Writing – review & editing, Funding acquisition, Formal analysis.

Declaration of Competing interest

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Data availability

Data will be made available on request.

Appendix I

Table A1
List of the reviewed literature and a summary of the findings (in total 41 articles were collected in which 39 were retrieved from databases and two articles were added manually after checking the references of the reviewed articles).

Row	Authors, Year	Title	Use Case, Sector, Country	Purpose	Key Findings
1	Alonso et al. (2020)	An intelligent Edge-IoT platform for monitoring livestock and crops in a dairy farming scenario	Overseeing farm inventory, Dairy cattle, Spain	Development of a smart farming platform by integrating Intern of Things (IoT) and Blockchain to monitor the state of dairy cattle and feed level in real-time.	The results demonstrated the ability of the platform in traceability and optimization of resources in the dairy industry with reduced costs associated with the transfer of data between the IoT and the remote cloud.
2	Bumblauskas et al. (2020)	A blockchain use case in food distribution: Do you know where your food has been?	Traceability and food authenticity, Egg supply chain distribution system, USA	Examined the application of blockchain and IoT-enabled technologies in an egg supply chain distribution system from the producer on the farm to consumers.	The case used (Bytable Inc., a blockchain food traceability company) provided proof of concept and ability to track the egg supply chain.
3	Cao et al. (2021)	Strengthening consumer trust in beef supply chain traceability with a blockchain-based human-machine reconcile mechanism	Traceability and food authenticity, Beef supply chain, Australia & China	Developed blockchain-based traceability to improve trust in the cross-border beef supply chain.	This mechanism enabled shared responsibilities between agriculture and supply chain actors and provided authentic tracking ability to consumers throughout the beef supply chain.
4	Casino et al. (2021)	Blockchain-based food supply chain traceability: a case study in the dairy sector.	Traceability and food authenticity, Dairy sector, Greece	Developed and tested secure architecture for dairy food traceability.	The proposed framework employed smart contracts within a private local blockchain system, leading to traceability-related operating cost reduction.
5	Chan et al. (2019)	A framework for traceable and transparent supply chain management for agri-food sector in Malaysia using blockchain technology	Traceability and food authenticity, Pepper, Malaysia	Provided a blockchain framework for investigating traceability and transparency in a case study of pepper in Malaysia.	Centralized supply chain management has created problems in the transparency and traceability of the current food supply chain. Blockchain technology can improve these shortcomings in a distributed manner.
6	Chen et al. (2020)	Electronic agriculture, blockchain and digital agricultural democratization: Origin, theory, and application	Traceability and Food Authenticity, Ecological farm, China	Examined the concept of "*digital agricultural democratization*" and proposed a blockchain-based electronic agriculture, using the case study of Beijing Liuminying Ecological Farm in China.	The blockchain network automatically collected and loaded data using smart devices, which led to solving asymmetric information problems and organic food tracking.
7	Feng, Wang, Duan, et al. (2020)	Evaluation on frozen shellfish quality by blockchain based multi-sensors monitoring and SVM algorithm during cold storage	Overseeing farm inventory, Shellfish, China	Investigation of blockchain-based multi-sensor monitoring system (incorporating HACCP) for collecting quality parameters and improving transparency for shellfish during storage.	Blockchain-based system provides reliable real-time monitoring of dynamic indicators which resulted in improved quality of frozen shellfish, and reduced losses.
8	Ferdousi et al. (2020)	A permissioned distributed ledger for the US beef cattle supply chain	Traceability and food authenticity, Beef cattle supply chain, USA	Proposed a smart contract-based blockchain supply chain management framework to solve the poor traceability in the beef cattle industry.	The model operates as a private consortium blockchain (supporting users' anonymity) allowing farmers to locally perform business transactions and transfer animal-related data to the new owners as required.
9	Garrard and Fielke (2020)	Blockchain for trustworthy provenances: A case study in the Australian aquaculture industry	Overseeing farm inventory, Prawn aquaculture industry, Australia	Investigated the potential of a blockchain ledger to record supply chain provenance and enable product	As a result of applying the blockchain technology, authors did not find a significant gain in the shrimp

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Table A1 (*continued*)

Row	Authors, Year	Title	Use Case, Sector, Country	Purpose	Key Findings
				tracking in a case study of the prawn aquaculture industry.	industry, although it helped to digitize the operations.
10	George et al. (2019)	Food quality traceability prototype for restaurants using blockchain and food quality data index	Traceability and food authenticity, Pork meat, India	Investigation of the major methods for food (pork meat) traceability in a restaurant case study.	Using blockchain helps traceability for food in restaurants and helps consumers to monitor the quality of food.
11	Grecuccio et al. (2020)	Combining blockchain and IoT: Food-chain traceability and beyond	Traceability and food authenticity, Fish food supply chain, Italy	Investigated the integration of Internet-of-Things devices with blockchain technology for traceability of fish supply chain.	The system allowed for developing decentralized applications while improving data integrity and authenticity.
12	Guido et al. (2020)	A framework for food traceability: Case study-Italian extra-virgin olive oil supply chain	Traceability and food authenticity, Olive oil, Italy	Provided a framework for tracking extra-virgin olive oil in the olive supply chain.	The traceable model increased the perceived value of the extra-virgin olive oil in the market (via digitizing documents, ensuring geographical origin and transparent information on a variety of the extra-virgin olive oils) which can be reused by small companies (due to the high similarity between the different chains of olive oil in Italy and other countries).
13	Hang, Ullah, and Kim (2020)	A secure fish farm platform based on blockchain for agriculture data integrity	Data security and integrity, Fish farm, South Korea	Presented a blockchain-based platform for fish farms to provide integrated and secured data.	Smart contracts and the use of blockchain reduce the risk of error or manipulation, as well as increasing the efficiency and usability of the proposed platform in the fish farm.
14	Iqbal and Butt (2020)	Safe farming as a service of blockchain-based supply chain management for improved transparency	Farm management and monitoring, Farm Management System, Canada	Proposed a blockchain-based supply chain management system that integrates different existing agricultural solutions (e.g., IoT) to protect products against animals via farm-based sensor nodes.	The farm management blockchain-based system can increase efficiency and share details of accidents and hazards with the farm owner. This system reduces costs and consumes less energy than conventional systems.
15	Kamble et al. (2020)	Modeling the blockchain-enabled traceability in the agriculture supply chain	Traceability and food authenticity, Agriculture supply chains, India	Identifying blockchain characteristics that improve agricultural supply chain performance (using literature and validation by experts).	The findings from the study suggest that, among the 13 identified characteristics of blockchain technology, traceability was the most significant enabler in the agricultural supply chain followed by auditability, immutability, and provenance.
16	Köhler and Pizzol (2020)	Technology assessment of blockchain-based technologies in the food supply chain	Traceability and food authenticity, Agricultural products such as tuna, coffee, mangos, and eggs, Denmark	Analyzed six cases of blockchain-based technology in the food supply chain by distinguishing direct and indirect impacts on the frameworks, techniques, knowledge, organization, and product. The authors provide new insights on how to implement blockchain technology and discuss the social and environmental consequences of this technology.	In comparison with a centralized non-blockchain system, the authors concluded that the direct impact of blockchain technology is increasing trust. Further direct influences incorporate transparency, traceability, and authenticity. However, they argue that no strong evidence exists yet on other indirect impacts, such as improved sustainability or reduced corruption.
17	Kumar & Iyengar, 2017#	A framework for blockchain technology in rice supply chain management	Traceability and food authenticity, Rice supply chain, India	Presenting a decentralized system based on blockchain framework to assure product safety in rice supply chain management.	Employing a blockchain framework for rice supply chain management. The system created a permanent history of the rice product from the manufacturer to traders, ensuring integral traceability and minimizing system errors.
18	Kumar, Kumar, and Anandh (2020)	Blockchain technology in food supply chain security	Data security and integrity, Food supply chain, India	Examined the idea of blockchain technology as a tool to improve food supply chain management and information security.	Blockchain-based supply chains increase efficiency, transparency, and lower cost. This system delivers real-time information to all parties, which leads to consumer confidence in food safety.
19	Leng et al. (2018)	Research on agricultural supply chain system with double chain architecture based on blockchain technology	Data security and integrity, Agricultural supply chain, China	Investigated the double chain architecture based on blockchain technology in agricultural supply chain management.	The double chain structure of the agricultural supply chain improves the security of the transaction and the privacy of enterprise information. It matches the supply and demand of agricultural businesses and enhances the credibility of the public service platform.
20	Li et al. (2020)	Convenience analysis of sustainable E-agriculture based on blockchain technology	E-commerce and trade efficiency, Fresh commodities, whole grains, and aquatic products, China	Data statistics are used to compare traditional electronic agriculture and e-agriculture based on blockchain.	Experimental data showed that blockchain-based e-commerce provides great convenience to farmers, increasing trade by 25% on average over traditional e-agriculture,

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Table A1 (*continued*)

Row	Authors, Year	Title	Use Case, Sector, Country	Purpose	Key Findings
					which can accelerate the development of sustainable smart agriculture.
21	Liu et al. (2020)	Investment decision and coordination of green agri-food supply chain considering information service based on blockchain and big data	Data security and integrity, Agri-food products, China	Examined the effect of the fusion of blockchain technology and Big Data on agricultural demand function, considering concerns for agri-food freshness and greenness.	Adopting a blockchain-enabled Big Data information system helps agri-food supply chain members gain more benefits.
22	Longo et al. (2020)	Estimating the impact of blockchain adoption in the food processing industry and supply chain	Traceability and food authenticity, Dairy industry, Italy	Proposed a potential application of Ethereum blockchain technology for supply chain monitoring and tracking purposes with a case study of the dairy industry.	The blockchain-enabled supply chain can provide advantages with a minimal impact on the product's consumer price; however, the costs will be increased as we move down the supply chain.
23	Malarvizhi (2019)	Interventions to scale-up palmpreneurship in Tamilnadu	Farm management and monitoring, Palm products (e.g., palm jaggery and palm sugar), India	Proposed the use of blockchain technology in planting palm trees and supply chain management of its products, such as palm jaggery and palm sugar.	The transformation of the edible palm products value chain into a blockchain-based supply chain increased the value, both in the domestic and export markets. It improved standardization, differentiation, and food safety.
24	Mao et al. (2018)	Innovative blockchain-based approach for the sustainable and credible environment in food trade: A case study in Shandong province, China	E-commerce and trade efficiency, Food supply chain China	Designed a blockchain-based food trading system to eliminate information asymmetry and to create a stable and credible business environment.	The application of blockchain for a sustainable and credible environment in the food trade can improve the profit of traders and increase the commercial value.
25	Nesarani et al. (2020)	An efficient approach for rice prediction from authenticated Block chain node using machine learning technique	Farm management and monitoring, Rice, India	Remote monitoring of optimum agricultural production by blockchain and IoT to analyze the essential environmental factors for optimum rice production using a machine learning algorithm.	Temperature and rainfall were essential environmental factors for better rice production and had a greater impact on rice production. The blockchain network (using sensors) improved secure communication of temperature, humidity, and rainfall data, along with the removal of incorrect data.
26	Rogerson and Parry (2020)	Blockchain: case studies in food supply chain visibility	E-commerce and trade efficiency, Fisheries, and Wine, UK	Investigating the impact of blockchain technology on the food supply chain by analyzing four case studies (i.e., AgriDigital, Techrock, TraSeable Solutions, and Demeter).	The findings from the cases show that blockchain most likely increases visibility and trust in supply chain management. The visibility presented via blockchain theoretically extends to auditors and authorities (though in practice full visibility blockchain-based solutions can be costly). It also reduces the risk of human error and counterfeit goods.
27	Salah et al. (2019)	Blockchain-based soybean traceability in agricultural supply chain	Traceability and food authenticity, Soybean, UAE †	Proposed a blockchain-based traceability method for soybean transactions throughout the food supply chain.	The proposed model builds on the utilization of smart contracts to govern interactions and increase the transparency and efficiency of soybean transactions across the supply chain network.
28	Surasak, Wattanavichean, Preuksakarn, and Huang (2019)	Thai agriculture products traceability system using blockchain and Internet of Things	Traceability and food authenticity, Agricultural products, Thailand	Designed an agricultural traceability system by using the Internet of Things and blockchain.	The proposed tracking system increased transparency and integrity through real-time data collection and secured database storage.
29	Syromyatnikov et al. (2020)	Agile supply chain management in agricultural business	E-commerce and trade efficiency, Small and medium-sized agri-food enterprises, Russia	Examining agile supply chain management methods using blockchain technology to create a network platform between small and medium enterprises of agricultural production in the agricultural trade.	The application of blockchain is more efficient than the traditional approach (providing digitalization and flexibility in agricultural supply chain management) and facilitates interaction among producers, consumers and intermediaries in the supply chain.
30	Tan et al. (2020)	Applying Blockchain for Halal food traceability	Traceability and food authenticity, Halal food supply chain, Malaysia	Investigated the challenges of Halal food supply chain traceability and proposed a new blockchain-based traceability framework in three distinct Halal supply chains.	Using smart contracts and blockchain technology, improved tracking processes of Halal food from the farm to the final consumer.
31	Tan and Ngan (2020)	A proposed framework model for dairy supply chain traceability	Farm management and monitoring, Dairy sector, Vietnam	Investigated the role of blockchain technology in improving food safety in the dairy sector.	The proposed framework improves dairy supply chain operational efficiency in terms of time, cost, and human resources.
32	Tian, 2017#	A supply chain traceability system for food safety based on HACCP, Blockchain & Internet of Things	Traceability and food authenticity, Agri-food in general, Austria †	Proposed a food supply chain traceability system based on blockchain and other technologies to	The suggested traceability system delivered real-time information of food safety status to all supply chain

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Table A1 (*continued*)

Row	Authors, Year	Title	Use Case, Sector, Country	Purpose	Key Findings
				provide an information platform for all food supply chain members.	members as well as reducing the risk of centralized information systems.
33	Tönnissen and Teuteberg (2020)	Analysing the impact of blockchain technology for operations and supply chain management: An explanatory model drawn from multiple case studies	Farm management and monitoring, Logistics in operational food supply chain, Germany	Used multiple case analyses to develop an explanatory model for blockchain technology in a food supply chain.	The results of the case studies indicated that blockchain applications have the potential to improve the logistics industry. However, this does not necessarily lead to disintermediation.
34	Tsolakis et al. (2021)	Supply network design to address United Nations sustainable development goals: a case study of blockchain implementation in Thai fish industry	Traceability and food authenticity, Fish industry supply chain, Thailand	Inconsistencies in data structures across the distributed data sources are considered as one of the main obstacles in achieving sustainability in the fish industry. The authors investigated the potential of blockchain technology in achieving sustainable development goals in the fish industry.	The results showed a great opportunity for a blockchain-based food supply chain with the integration of IoT reducing the information asymmetry and improving the flexibility between the data systems across the fish industry. The blockchain-based model contributes to the goals of sustainable development and reducing illegal fishing.
35	Violino et al. (2020)	A full technological traceability system for extra virgin olive oil	Traceability and food authenticity, Virgin olive oil, Italy	Proposed an electronic traceability prototype in the Extra Virgin Olive Oil supply chain (EVOO).	The proposed technology can provide guarantees for consumers (traceability aspect) and help farmers to achieve precision farming by mechanized harvesting.
36	Violino et al. (2019)	Are the innovative electronic labels for extra virgin olive oil sustainable, traceable, and accepted by consumers?	Traceability and food authenticity, Virgin olive oil traceability technology systems, Italy	Examined consumer preference for three traceability technology systems (Near Field Communication, tamper-proof device plus Radio Frequency Identification, and blockchain-based system with QR-code) for the sustainable production of olive oil.	About 94% of consumers agreed with the implementation of such technologies, and about 45% chose a blockchain tracing system with a QR code (Due to the easy use of QR codes).
37	Yang et al. (2021)	A trusted Blockchain-based traceability system for fruit and vegetable agricultural products	Traceability and food authenticity, Fruit and Vegetable, China	Designed a traceability blockchain-based system for the storage and querying of product information in the fruit and vegetable sector.	The proposed system provided tamper-proof and decentralization features which improved the query efficiency, and security of private information and ensured the authenticity (reliability) of data in fruit and vegetable supply chain management.
38	Zhang (2020)	The innovation research of contract farming financing mode under the blockchain technology	E-commerce and trade efficiency, Agri-food in general, China†	Studied the application of blockchain technology in the financing system for agricultural orders.	The blockchain system will greatly improve the problem of information asymmetry and will enable financial institutions/insurance companies to exchange information in real-time.
39	Zhang, Han, et al. (2020)	A storage architecture for high-throughput crop breeding data based on improved blockchain technology	Farm management and monitoring, Storing crop breeding data, China	Designed a storage platform (Golden Seed Breeding Cloud Platform) for storing high-throughput crop breeding data by using improved blockchain technology.	This storage architecture significantly increases the efficiency of the platform, especially when the amount of data is large.
40	Zhang, Sun, et al. (2020)	Blockchain-based safety management system for the grain supply chain	Traceability and food authenticity, Grain supply chain, China	Proposed a system architecture in grain supply chain management using blockchain technology. The suggested model included a multimode storage mechanism that aggregates chain storage data.	Compared to traditional grain storage systems, the blockchain-based system is more secure and reliable, enabling dynamic process tracking to ensure food quality.
41	Zhang et al. (2021)	Development and assessment of blockchain-IoT-based traceability system for frozen aquatic product	Traceability and food authenticity, Frozen aquatic products, China	Proposed a traceability system for frozen aquatic products based on blockchain-IoT to overcome the shortcomings of conventional tracing systems, such as inefficient centralized data management and information tampering.	The proposed system provided more reliable information tracking and improved traceability performance, as well as improved aquatic food logistics when compared with traditional systems.

Note: two articles incorporated in Table A2 are added manually (Kumar & Iyengar, 2017; Tian, 2017).

† The country is retrieved from the first author's affiliation.

Table A2
Blockchain characteristics retrieved from literature (e.g., English & Nezhadian, 2017; Hackius & Petersen, 2017; Haswell & Storgaard, 2017; Kim & Laskowski, 2018; Liang, 2020; Motta et al., 2020; Rana et al., 2021).

Principal Characteristics	Sub-dimensions	Enablers	Description

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Table A2 (*continued*)

Principal Characteristics	Sub-dimensions	Enablers	Description
Trust Evoking	Transparency	Shared & public interaction	**Distributed consensus** mechanism increases **trust** aimed at network users (Chen et al., 2019; Mainelli & Smith, 2015; Swan, 2016; Swanson, 2015; Walport, 2016).
		Low friction in providing information	Blockchain **reduces the friction of imperfect information** and facilitates the smooth flow of information. Hence, the process becomes more transparent (English & Nezhadian, 2017; Kim & Laskowski, 2018).
	Immutability	Peer verification of transactions	Verification of the transactions takes place by **consensus algorithm** (Chen et al., 2019; English & Nezhadian, 2017; Liang, 2020).
		Enhanced security through cryptography	All records are hashed and **cryptographically** sealed. Cryptography is a rather complex mathematical algorithm that functions as a firewall against tampering (Liang, 2020). Any validated records are **irreversible** and cannot be changed (Chen et al., 2019; Liang, 2020).
Decentralization	Redundancy	Distributed ledger (reliability)	Transactions are continuously **replicated** on all or several groups of nodes in a network (Chen et al., 2019; Liang, 2020).
	Versatility	Open source (scalability)	The data stored in a blockchain system is **publicly accessible** for all users, and every user can use the blockchain platform to develop any new application (Chen et al., 2019; Vos, 2016).
		Anonymity of participants	The identity of the participants is either **anonymous** or pseudonymous (Chen et al., 2019; English & Nezhadian, 2017; Hackius & Petersen, 2017; Viriyasitavat & Hoonsopon, 2019).
System Integration	Automation	Smart contracts	The actions can be effortlessly automated via **smart contracts** (Kim & Laskowski, 2018).
		A platform for real-time integration	**Integrating** with real-time applications, such as the Internet of Things, sensors, and Radio Frequency Identification (Lin et al., 2017).
	Remittance	Faster settlement	Blockchain makes the **payment process more transparent and quicker** by using cryptocurrencies or 'stablecoins' as an intermediary currency (Rühmann et al., 2020).
		lower transaction fees	Unlike conventional channels, blockchain remittance facilitates faster financial transactions between sender and receiver with **lower transaction fees**.

Table A3
Selected review articles on blockchain and food supply chain management.

Authors	Article title	Purpose	Method	Sample/Year (Databases)	Key Findings/Limitations
Giganti, Borrello, Falcone, and Cembalo (2024)	The impact of blockchain technology on enhancing sustainability in the agri-food sector: A scoping review	Investigation of blockchain applications in the agri-food sector and the role of this technology in promoting sustainability in this sector.	Scoping review	72/2022 (Scopus)	Blockchain technology can enhance economic sustainability by reducing transaction costs and improving transparency, environmental sustainability by lowering carbon emissions, managing waste, and monitoring environmental impacts, and social sustainability by improving food safety and boosting consumer confidence. However, further research is needed to tackle challenges such as identifying barriers, developing localized solutions, understanding consumer trust factors, enhancing crisis resilience, assessing environmental impacts, and ensuring fair market access.
Ordoñez, Gonzales, and Corrales (2024)	Blockchain and agricultural sustainability in South America: a systematic review	Identifying the advantages and disadvantages of the current use of blockchain to support sustainable agriculture and agribusiness, with a focus on its application in South America.	Systematic literature review	17/2023 (Web of Science and Scopus)	Blockchain is becoming an important tool in sustainable agriculture by promoting food safety and providing verifiable product information to consumers. However, high initial costs, training requirements, scalability issues, dependence on a stable internet, technical complexity, privacy concerns and cybersecurity issues prevent widespread adoption. Future research should focus on these obstacles.
Fiore & Mongiello, 2023	Blockchain technology to support agri-food supply chains: a comprehensive review	Identify the current state of the art in blockchain technology and smart agri-food and create appropriate foundations to identify the gaps and trends in this research area as well as future research directions.	Comprehensive review	183/2022 (IEEEXplore, ACM, and Science Direct)	Blockchain technology can increase brand identity and sales by ensuring high-quality products, managing goods efficiently and transparently, and feeling protected and informed by learning more about the supply chain via QR codes. Further research is

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Authors	Article title	Purpose	Method	Sample/Year (Databases)	Key Findings/Limitations
					needed to improve stakeholder education, integrate additional technologies for scalability and reliability, and develop tools to help developers choose the best blockchain platforms.
Peng et al. (2023)	A review on blockchain smart contracts in the agri-food industry: current state, application challenges and future trends	Reviewing and highlighting the state of research, challenges and future development trends of blockchain smart contracts in the agri- food industry.	Comprehensive review	78/2023 (Web of science, Derwent Innovations Index, KCI-Korean Journal Database, MEDLINE, FSTA - Food Science Database and SciELO Citation Index)	Blockchain smart contracts in the agrifood industry offer increased security, confirmation of data rights and automated data collection, recording and analysis. However, the study lacks an informatics perspective, only includes literature up to August 2022, and covers a limited scope with potentially unaddressed comparisons and issues.
Yogarajan et al. (2023)	Exploring the hype of blockchain adoption in agri-food supply chain: a systematic literature review	Investigating the effect of blockchain adoption on the agri-food supply chain.	Systematic literature review	27/2022 (Web of Science)	Blockchain enhances food traceability, transparency, safety, supply logistics, integrity, environmental awareness and reduces food waste. As a limitation, this study excludes conceptual studies and focuses on a specific inclusion/exclusion approach that limits the scope of digitalization and sustainability related to the adoption of blockchain technology.
Alobid, Abujudeh, and Szűcs (2022)	The role of blockchain in revolutionizing the agricultural sector	Reviewing blockchain technology, its applications and key advantages in agriculture.	Systematic literature review	79/2021 (Web of Science)	A Transparent secure system, reassuring investors, immediate transactions through smart contracts, and easy trade on exchanges are benefits of using blockchain in agriculture. Complexity and operating cost at the micro level, as well as the regulation that should be developed to govern the safe use of this growing technology, are challenges of blockchain technology in the agriculture business.
Pandey et al. (2022)	Blockchain technology in food supply chains: Review and bibliometric analysis.	Reviewing the application of blockchain technology in the food supply chain, challenges and potential solutions to deal with the problems ahead.	Systematic literature review	150/2021 (Scopus)	Blockchain technology in integration with IoT devices increases transparency and confidence among actors in the food chain and reduces risk in the food supply.
da Silveira et al. (2021)	An overview of agriculture 4.0 development: Systematic review of descriptions, technologies, barriers, advantages, and disadvantages	Identifying barriers and advantages/disadvantages of the theory of agriculture 4.0.	Systematic literature review	50/2020 (Scopus, Science Direct, and Web of Science)	Using the technologies of Agriculture 4.0 improves the accessibility of data, harvesting of agricultural commodities, and the user's sustainability image. Yet there are still technical, economic and environmental issues that hinder the development of this technology.
Dey and Shekhawat (2021)	Blockchain for sustainable e agriculture: Literature review, architecture for data management, and implications	Investigating the potential of integrating blockchain and IoT to improve the agricultural value chains.	Content-analysis-based literature review	75/2021 (Google Scholar, Scopus, and Web of Science)	Integrating blockchain technology with IoT improves the agricultural value chains in terms of data storage validity, real-time decision-making, data sharing, certified registration using smart contracts, transparent and authentic data.
Li et al. (2021)	Blockchain in food supply chains: a literature review and synthesis analysis of platforms, benefits and challenges.	Investigating the benefits and challenges of using blockchain in the food supply chain.	Systematic literature review	74/2021 (Web of Science, Business Source Premier, Science Direct, Academic Search Premier, and ProQues)	Blockchain technology increases the transparency of transactions, food safety as well as food quality. Also, this technology improves the efficiency of the food supply chain by reducing operating costs and waste. However, there are still

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Table A3 (*continued*)

Authors	Article title	Purpose	Method	Sample/Year (Databases)	Key Findings/Limitations
					challenges to overcome such as high cost and lack of regulations particularly regarding data governance.
Vu et al. (2021)	Blockchain adoption in food supply chains: a review and implementation framework.	Exploring the drivers and obstacles in the implementation of blockchain technology in the food supply chain.	Systematic literature review	69/2020 (Web of Science, Scopus, and EBSCo)	Challenges such as scalability, regulations and incentivization were identified as challenges for future research.
Demestichas et al. (2020)	Blockchain in agriculture traceability systems: a review	Reviewing the empirical applications of blockchain for enabling traceability in the management of agriculture supply chains.	Narrative literature review	–	Despite its limitations (incl. regulation interfaces, data ownership, and scalability) blockchain-based traceability creates a superior credibility that contributes to a more sustainable food industry.
Duan et al. (2020)	A content-analysis based literature review in blockchain adoption within food supply chain	Investigated the benefits of blockchain and the challenges in the adoption of this technology in the food supply chain.	Content analysis-based literature review	26/2018 (Web of Science, Scopus, and EBSCo)	There are four benefits of blockchain technology adoption in the food supply chain, including food traceability, improving system efficiency, and the ability to integrate with other technologies.
Lin et al. (2020)	Blockchain technology in current agricultural systems: from techniques to applications	Identifying existing agricultural blockchain applications with necessary technical aspects.	Review	–	Blockchain technology leads to achieving efficiency and integrity of agricultural applications. There are several key challenges in the current agricultural use of blockchain such as scalability, integration with existing legacy systems, security, and privacy.
Torky and Hassanein (2020)	Integrating blockchain and the internet of things in precision agriculture: Analysis, opportunities, and challenges	Reviewing smart applications of blockchain (integrated with IoT) in developing precision agriculture.	Narrative literature review	–	Potential blockchain applications in agriculture include farm overseeing, land registration, food safety, and real-time remittance for small farms. Main challenges are energy consumption and complex technical issues in multi-chain management designs.
Yadav and Singh (2019)	A Systematic Literature Review of Blockchain Technology in Agriculture	Detecting the current blockchain research trends in the field of agriculture.	Systematic literature review	29/2019 (IEEE Explore, Taylor and Francis, ScienceDirect, Springer, emerald, Web of Science, google scholar, Scopus)	Blockchain-based research in agriculture mainly focused on traceability, security design, and blockchain as an information system. The limitations of this technology are security problems against attacks, the low speed of blockchain-based transactions, and high-power consumption.
Zhao et al. (2019)	Blockchain technology in agri-food value chain management: a synthesis of applications, challenges, and future research directions	Overviewing of the recent advances, main applications, and challenges of blockchain technology in the food supply chain.	Systematic literature review	71/2018 (Science Direct, Web of Science, Scopus, Taylor & Francis Online, Wiley Online Library, Emerald, Google Scholar, and IEEE Xplore)	Blockchain technology along with recent developments in IoT can improve the agricultural value chain from four aspects of traceability, information security, manufacturing, and sustainable water management.
Bermeo-Almeida et al. (2018)	Blockchain in Agriculture: A Systematic Literature Review	Reviewing relevant research on blockchain technology in agriculture, main contributions, and benefits of applying blockchain in agriculture.	Systematic literature review	10/2018 (IEEE Xplore Digital Library, ACM Digital Library, ScienceDirect, Springer, Google Scholar, Web of science)	The review identified advantages of blockchain use cases such as transparent information, improved data reliability, and faster and more efficient operations.

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