

Applying blockchain technology to improve agri-food traceability: A review of development methods, benefits and challenges

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ABSTRACT

Traceability plays a vital role in food quality and safety management. Traditional Internet of Things (IoT) traceability systems provide the feasible solutions for the quality monitoring and traceability of food supply chains. However, most of the IoT solutions rely on the centralized server-client paradigm that makes it difficult for consumers to acquire all transaction information and to track the origins of products. Blockchain is a cutting-edge technology that has great potential for improving traceability performance by providing security and full transparency. However, the benefits, challenges and development methods of blockchain-based food traceability systems are not yet fully explored in the current literature. Therefore, the main aim of this paper is to review the blockchain technology characteristics and functionalities, identify blockchain-based solutions for addressing food traceability concerns, highlight the benefits and challenges of blockchain-based traceability systems implementation, and help researchers and practitioners to apply blockchain technology based food traceability systems by proposing an architecture design framework and suitability application analysis flowchart of blockchain based food traceability systems. The results of this study contribute to better understanding and knowledge on how to improve the food traceability by developing and implementing blockchain-based traceability systems. The paper provides valuable information for researchers and practitioners on the use of blockchain-based food traceability management and has a positive effect on the improvement of food sustainability.

Keywords: traceability; blockchain technology; security and transparency; food sustainability

1 Introduction

The food chain needs to become more sustainable in order to improve consumers' trust and purchase willingness. Tracking and authenticating the information throughout the whole food supply chain is critical for identifying and addressing sources of contamination, which contributes to sustainability management in agri-food chains (Galvez et al., 2018; Olsen et al., 2018, Zhao et al., 2017; Sun et al., 2017; Bosona et al., 2013). Traditional Internet of Things (IoT) traceability systems can monitor and store the specific information in all stages of production, processing, distribution and consumption by using Radio Frequency Identification (RFID), Wireless Sensor Network (WSN), Near Field Communication (NFC) technology, etc. It can provide valuable information for the food quality monitoring and traceability. However, it is based on the centralized server-client paradigm, the stakeholders and consumers have to rely on a single information point to store, transmit, and share the traceability information (Khan et al., 2018; Mohanta et al., 2018; Cai et al., 2014). As a result, most consumers have difficulty in acquiring full transaction information and tracking the origins of products (Velis et al., 2013; Imeri & Khadraoui, 2018). Consumers and food chain participants need to be fully informed about the product life cycle (PLC) to assure that products are safe, sustainable, and of high quality (Hassan et al., 2019; Banerjee et al., 2018; Bozic et al., 2016). However, current food traceability systems are not very effective to build trust mechanisms among participants in traceability chain (Zhao et al., 2019; Helo et al., 2019; Khan et al., 2018). A safe and effective information management of agri-food is urgently required for improving food traceability.

The solution to address the food safety and quality concerns is to improve traceability transparency, security, durability, and integrity (Feng et al., 2019; Tsang et al., 2018; Helo & Hao, 2019; Banerjee et al., 2018; Li et al., 2017). Therefore, data privacy and tamper-proof concerns are essential in the agri-food traceability, which have become an urgent issue for farmers, producers, cold chain managers, governments and consumers (Zyskind et al., 2015; Caro et al., 2018). Blockchain technology is regarded as a promising technology that can help to build trust mechanisms for solving the transparency and security issues, no single party in the supply chain can alter existing information. As a distributed and decentralized technology, blockchain is a set of time-stamped blocks that are linked by a cryptographic hash. It has been widely accepted as a solution to the underlying trust and security issues in information transparency and prevention of tampering with (Ølnes et al., 2017; Galvez et al., 2018; Andoni, et al., 2019; Sikorski et al., 2017; Yong et al., 2019).

Although blockchain is considered as a potentially breakthrough technology, there are several research gaps because studies on the development and applications of food traceability are still seriously lacking. There are very limited understanding on how the

block chain technology can be used to improve the food traceability performance through the full information transparency and security dimension of food chains (Kim et al., 2017; Yiannas et al., 2018), and what the key benefits and challenges are in terms of the practical operations, system infrastructure, interoperability and standardization issues. There is also a need to understand blockchain applications on policy support, participant collaboration and trust, and technical integration (Lin et al., 2017; McLean et al., 2016).

Therefore, this paper aims to address these significant research gaps by answering the following key questions:

1. How can blockchain technology provide better solutions to address the food traceability concerns in terms of full information transparency and security in food supply chains?
2. How can blockchain-based IoT traceability system be implemented for food traceability management?
3. What are the main benefits and challenges in implementing blockchain technology in managing food traceability?

Therefore, this research reviews the blockchain technology characteristics and functionalities, identify blockchain-based solutions for addressing traceability trust mechanisms, highlight the benefits and challenges of blockchain-based traceability systems implementation, and help researchers and practitioners to understand and apply blockchain technology in food traceability by proposing an architecture design framework and application feasibility analysis flowchart. The results contribute to the further improvement of the traceability transparency and efficiency and enable better security of the quality and safety of the food chain. The paper provides valuable information for researchers and practitioners on the use of blockchain-based food traceability management and has a positive effect on the improvement of food sustainability (George et al., 2019; Kamilaris et al., 2019).

The rest of the paper is organized as following. Section 2 explains the research methodology; section 3 is literature review. Based on the literature, section 4 proposes an architecture design framework and application requirement analysis of blockchain-based food traceability systems; section 5 explores the potential use with pilot application examples reported in the literature; section 6 discusses the benefits and challenges followed by the conclusion in section 7.

2 Research methodology

To achieve the research aim and address the key research questions, firstly this study conducts a comprehensive literature review to understand the blockchain technology characteristics, current development and applications and the solutions for

addressing food traceability concerns. Secondly and most importantly, based on the literature review, this study proposes an architecture design framework and suitability and sustainability evaluations of blockchain-based food traceability systems. Thirdly, two pilot application examples reported in the literature are used to demonstrate the development processes of blockchain in two different types of food chains.

Literature review includes relevant search terms and literature resource selection because it is important to select the most relevant and quality publications. As the blockchain is a relatively new phenomenon, the time period for literature review is 2005-2019. The search focuses on blockchain in general and blockchain for food traceability in particular.

The search terms “blockchain AND information security” or “blockchain AND food traceability/supply chain” or “smart contract AND agriculture/food ” or “digital AND food traceability/supply chain ” are used, The search covers the title/ abstract/ keyword. The literature sources identified include online databases from Google Scholar, ScienceDirect (Elsevier), Web of Science, ProQuest (ABI/INFORM), IEEE Xplore, CNKI (China National Knowledge Internet) and other online resources.

For retrieval and classifying the available literature, the following criteria was adopted (Casino et al., 2018; Zhang et al., 2011):

1. Distribution of publications over time and thematic type;
2. The literatures were selected through search terms that classified and ranked the most significant international journals;
3. If two or more papers had the same theme and are published in the same journal, the latest published paper was selected.

The results of relevant publications from 2005 to 2019 are shown in Fig. 1. The upward trend of publications indicates that research interest in blockchain technology has dramatically increased in the last three years.

The literature analysis reveals that there are fewer published papers on the successful real-world implementations of blockchain-based food traceability cases. To demonstrate how blockchain technology can be applied in different types of food chains, this study uses two pilot application examples reported in the literature. These two examples are based on the plant-based and poultry-based food chains in China. They represent the typical agri-food traceability chains and are considered suitable as demonstration examples.

Fig. 1. Results of literature search according to the thematic area identified

3 Literature review

Demands for traceability information by firms, governments and consumers has increased significantly due to the food safety and quality issues. Traceability

information can be traced, coordinated, and collected from business transactions and IoT-enabled devices such as Radio Frequency Identification (RFID), Wireless Sensor Network (WSN), QR code, NFC, etc. Although information can be collected in real time, information sharing relies on the centralized platform control, and there is no guarantee of preventing data tampering (Velis et al., 2013; Imeri et al., 2018). It is believed that blockchain technology can build trust mechanisms for information transparency and security and realize the exchange of value information in the traceability management process.

The literature on blockchain-based traceability identifies the important impact on the agri-food supply chain, including transparency and accountability (Tama et al., 2017; Kshetri 2018), traceability and fraud prevention (Jin et al., 2017), security and authentication cybersecurity and protection etc. (Galvez et al., 2018; Kshetri 2018; Banerjee et al., 2018).

Many scholars proposed different blockchain applications in traceability systems in combination with other emerging technologies, such as RFID, IoT, NFC, cloud computing, and big data. For example, (Zhang et al., 2017) reported a traceability system that applied the blockchain combined with NFC for tracking agri-food. It was believed that the system could provide higher transparency and security (Zhang et al., 2017). A blockchain based wine traceability chain was proposed by (Iansiti et al., 2017). The transaction is visible to wine chain participants, such as the grape plant, wine processing, logistics and consumption, thus it provides secure, transparent and accurate information sharing. Their research demonstrates that the application of blockchain-based traceability systems is beneficial to the agri-food traceability. Based on the comprehensive literature review, table 1 summarizes the blockchain solutions for addressing the traceability issues.

Table 1 Blockchain solutions for addressing the traceability issues

3.1 Operational framework of blockchain-based traceability

Based on the literature analysis, the study presents an operational framework of blockchain-based food traceability system as shown in Fig. 2.

As a distributed and decentralized technology, blockchain is a set of time-stamped blocks that are linked by a cryptographic hash. It has emerged as a decentralized public consensus with the digital distributed databases to coordinate transaction activities (Puthal et al., 2018; Fernández-Caramés & Fraga-Lamas, 2018; Bozic et al., 2016). Blockchain-based traceability are safer, more transparent, traceable and efficient. This has raised the demands to trace the products information from farming to sales. It contributes to more effectively material and information flow in traceability business. Therefore, blockchain will improve the information security and transparency, and contributes sustainable traceability management by means of IoT-based devices for the

information acquisition and persistence of agri-food products (Ølnes et al., 2017; Galvez et al., 2018).

Fig. 2. The operational framework of blockchain-based traceability

3.2 Operational mechanisms of blockchain-based traceability

In this section, the operational mechanisms of blockchain-based traceability are described as shown in Fig. 3. As blockchain is a shared, distributed and tamper proof digital ledger that consists of immutable digital record data in a package called a block (Kakavand et al., 2017). Transactions are contained in blocks linked together through a series of hash pointers. They are distributed to a peer-to-peer network consisting of participants. Blockchain relies on the consensus mechanism to establish the trust of nodes. Each node in the decentralized system has a copy of the ledger. Participants confirm changes with one another and transactions are verified through consensus. For example, smart contracts allow users to complete data exchange or transactions without third-party trust institutions (Galvez et al., 2018). Successful transactions cannot be tampered with.

In the agri-food traceability business process, all traceability transactions information could store in the blockchain, and information needs to be verified, in a way that is permanent and unalterable. Therefore, it can not only cut off middlemen, reduce costs, improve speed and coverage, but also provides greater transparency and traceability for consumers (Aiello et al., 2015; Galvez et al., 2018).

Fig. 3. Operational mechanism of blockchain technology

3.3 Functional characteristics of blockchain-based traceability

Blockchain is an innovative application of distributed data storage, peer-to-peer transmission, consensus mechanism, encryption algorithm, and other information technologies (Khan et al., 2018; Zheng et al., 2017). The main functional characteristics of blockchain are as follows:

- Decentralized and trustless network

Blockchain is composed of many nodes to form peer-to-peer network. There is no centralized equipment and management mechanism. The destruction or loss of any node will not affect the operation of the whole system, which has excellent robustness. The data are shared among the participants (Bahga et al., 2016; Bosona et al., 2013). They can validate the data by digital signature technology without the need for a centralized authority and mutual trust.

- Smart contracts in traceability business process

Transactions in blockchain can be automated through smart contracts. Certain business rules are deployed on the blockchain, allowing participants to trace business

process and validate contract rules (Andoni et al., 2019; Sikorski et al., 2017). It contributes to data sharing and continuous process improvement among supply chain participants. In addition, smart contracts can ensure that the parties are prevented to create error records, especially when combined with IoT devices.

- Consensus mechanism

The consensus mechanism is the way in which all parties in the blockchain reach consensus and determine the validity of a record. This is done by a computer system that uses a cryptographic proof (Tian et al., 2017). The consensus mechanism can prevent data tampering in traceability process.

- Transaction transparency and anonymity of the traceability chain

The rules and all information about the operation of the blockchain are open and transparent to participants with access to the blockchain network (Ølnes et al., 2017; Wang et al., 2019). Each transaction is visible to all nodes at all levels and each participating node is anonymous. Therefore, it can ensure traceability, reliability, security and information timeliness of agri-food products, and realize transparency management from harvest, storage, distribution to sales.

- Data tamper-proof and traceable

Transaction information for all participants in the supply chain is recorded in the block and data records cannot be tampered with and deleted (Xu, et al., 2019; Dorri et al., 2017). Thus, information exchange activities can be queried and traced. The transparent data management provides a trusted way for audit checking, operation logging, logistics tracking and other operational activities.

- High reliability of systems and data

Blockchain technology enables each node in a blockchain network to obtain a complete data in the form of distributed data storage. The data are maintained jointly by all nodes. For example, changes to the database on a single node are not valid unless more than 51% of the nodes in the whole supply chain are controlled (Lin et al., 2017; Galvez et al., 2018).

4 Development and evaluation methods for blockchain-based food traceability system

4.1 Requirements analyses of blockchain-based traceability system

Quality traceability requirements in supply chain of agri-food products are the most important concern of the stakeholders. The key to the performance evaluation of blockchain-based quality traceability system is to meet the stakeholders' traceability requirements in the agri-food chain. Based on the literature analysis, a set of blockchain enabled quality traceability requirements are analysed and presented in table 2.

Table 2 Requirements analysis of the blockchain-based traceability system

- **Technical requirements in the agri-food supply chain**

Essential technical requirements of quality traceability system are to be able to operate in a trustless environment. The traceability information needs to be secure, reliable and transparent. Blockchain-based traceability enables distributed data sharing. Therefore, using blockchain technology can trust and security issues in information transparency and prevention of tampering.

- **Performance requirements**

The agri-food supply chains are constantly growing that require more resources for computing power. Due to reliance on real-time data transmission and sharing by IoT devices, the nodes are needed to validate transactions and blocks (Bozic et al., 2016; Fernández-Caramés & Fraga-Lamas, 2018). Therefore, storage capacity, scalability, stability and processing ability are significant performance indicators. The blockchain system needs low power consumption, high speed and secure performance of blockchain-based quality traceability system.

4.2 Architecture design of blockchain-based food traceability system

A general IoT-based quality traceability system utilizes a centralized database that stores all products information concerning quality characteristics when it starts from farming to consumption. However, the non-tampering characteristics of blockchain provide a more effective solution for the anti-counterfeiting and quality traceability of agri-food products (Zhao et al., 2019; Helo et al., 2019). This study proposes a blockchain-based quality traceability architecture to improve transparency and security of the transaction information throughout the whole traceability process as shown in Fig. 4. The proposed architecture consists of the business layer, IoT layer, blockchain layer and application layer.

Fig. 4. Architecture of blockchain-based food traceability system

- **Business layer:** this layer covers the various business activities from farming to consumption of the whole supply chain. Each enterprise in the supply chain can control and manage the agri-food traceability information. However, current agriculture and transactions in agri-foods traceability have never fully undergone a digital transformation (Bastas et al., 2018). The agri-food chains need the support of the digital ledger technology, which has the greatest potential to integrate and manage each process and transaction throughout the traceability chain in real time.

- **IoT traceability layer:** in this layer, traceability information includes quality information, processing data, assets, logistic and transaction information. Data is recorded with connected devices (such as identity chips, RFID, WSN, barcode technology). Various sensors will be used to collect and transmit automatically and continuously the ambient information about temperature, humidity, O₂, CO₂, etc. These

connected devices are able to communicate with ledgers in blockchain (Bechini et al., 2008; Imeri et al., 2018).

- **Blockchain layer:** this layer aims to facilitate information transparency and improve security of agri-food traceability. With the quality data, smart contracts can implement real-time quality monitoring and control in blockchains. With the logistics data, smart contracts are able to plan logistics automatically (Kshetri, 2018; Saberi et al., 2018). The system is also able to provide the retailer and consumers with a way to indelibly record a list of transactions indicating how products have flowed through a commercial network, from producers to processors to distributors to grocers—and finally, to consumers, thus, meeting any of accountability and traceability requirements.

- **Application layer:** this layer is the intermedia layer of the interaction between the actors in the traceability chain and the information platform. The actors can view the recording of the whole process of logistics, information flow and capital flow through the application layer.

4.3 Suitability and sustainability evaluations of blockchain-based traceability system

The suitability evaluation of the blockchain-based traceability is very important for the users and traceability managers. The purpose is to improve the various strategic supply chain objectives of traceability management. System evaluation provides the optimization of process and quality management control of agri-food supply chain. Combining the information of the blockchain and the system resources operation consumption, the detailed performance evaluation criterion is summarised in table 3. Based on the performance evaluation criteria analysis, the study proposes a suitability and sustainability application analysis flowchart for blockchain-based traceability system as shown in Fig 5.

Table 3. Performance dimension in achieving the traceability objectives

Fig. 5. A flowchart of suitability and sustainability application analysis for blockchain-based traceability system

5 Applying blockchain technology in sustainable food traceability management

The traceability data in the blockchain can be accomplished at each traceability business process. This section describes the potential uses of blockchain in sustainable traceability management of agri-food products.

5.1 Blockchain-based IoT applications in traceability business stages

Stage 1: farming

Farming is the first link in the agri-food traceability process. IoT smart devices can collect and transmit the traceability data needed in the business process. The

traceability information available can store blockchain-based traceability system. The traceability information may include farming background environment (e.g. soil, water, temperature and humidity quality), farming staff, date, time, origin and application of drug variety, irrigation, fertilizing and pesticides (Caro et al., 2018; Bastas et al., 2018). A new transaction can be started between the farmer and processor and create records in the blockchain.

Stage 2: harvesting

Agri-food products are harvested at the suitable time. Farmers store the traceability information in the business process into the blockchain-based traceability system including date, time and weigh scales. After harvesting, they are mostly transported to the processing plants for further processing by the refrigerated truck.

Stage 3: processing

The processing stage has great impact for the quality and safety of agri-food products. The traceability information includes processing condition such as processing equipment, time, batch transformations, package information, disinfection method, operators and final product tags information (Feng et al., 2019). In this stage, operators store the traceability information into the blockchain-based traceability system by scanning its tag.

Stage 4: logistics & cold storage

This stage can be complex and costly. The cold storage should be equipped with an effective micro-ambient (temperature, RH, O₂, and CO₂) monitoring system. The use of IoT sensor devices can obtain the relevant traceability information of logistics & cold storage. the deployment of ambient and GPS sensors in the areas of refrigerated containers can monitor and collect the logistics & cold storage environment information to be stored in the blockchain system, such as: trucks and products data, ambient parameter, storage location, storage time, operator method (Galvez et al., 2018). This system can also help the managers to make decisions for reducing losses or spoilage.

Stage 5: consuming

Sold products information are stored in the blockchain. The information may include product name, sale time, shelf life, price, etc. Consumers can easily retrieve the history of the products before purchasing.

5.2 Application examples

5.2.1 Example 1 – Blockchain-based traceability of plant food production chain

This example is reported by (Galvez et al., 2018). In the plant production process, smart contract can record all the production information including seeding purchase, planting, growing to consumption. RFID and IoT devices are used to track environment

and quality information. Then the information can upload to the blockchain. The blockchain-based traceability process of plant is shown in Fig. 6.

Fig. 6. The blockchain-based traceability process of plant food production

Such traceability information of plant may include seeding quality, production conditions, fertilization and pesticides condition, growing data, cold storage environment (temperature, humidity, gas etc.), and sales information. Consumers scan the bar codes to retrieve the information from farming, production, processing to end-consumption. The information is transparent throughout the plant production process, and once it is uploaded into the blockchain that can prevent to be tampered with. Therefore, blockchain-based traceability process of plant food production can not only improve the traceability and sustainability management, but also increase consumers' trust and purchase willingness (Matzembacher et al 2018).

5.2.2 Example 2 – Blockchain-based traceability of poultry

This example is a project of collaboration between Ali cloud and ZhongAn Technology Company that aims to realize the traceability transparency of chicken poultry supply chain applying blockchain technology (Adele Peter, Fast Company 2017).

The application process is shown in Fig. 7. Every chicken wears a chicken card from farming, slaughtering, refrigeration, packaging, transportation and reaching the consumers, which can automatically collect the location and movement data of chickens and upload them to the blockchain in real time. The traceability information includes breed of chicken seedlings, environmental sensors data (temperature, RH, air, light, etc.), weigh, health, growth cycle, slaughtering data, quarantine, sales information etc. The information is stored in the blockchain for the life cycle (LC). Consumers can scan the QR code on the chicken card and see the growth and circulation of chicken data (Aung et al., 2014).

Fig.7. Blockchain-based traceability process of chicken poultry

6. Benefits and challenges in blockchain-based sustainable traceability management

6.1 Benefits

The blockchain has a far-reaching impact on the research and practice for agri-food product traceability. It could overcome the information security and transparency concerns when integrated with IoT devices. The potential benefits of the blockchain-based traceability management are summarised in Fig. 8.

- Informational security

The information is stored in the blockchain-based traceability system is more reliable due to the consensus mechanism. This enhances transaction data integrity and security (Puthal et al., 2018; Ølnes et al., 2016; Conoscenti et al., 2016). Furthermore, it provides high levels of immutability, information integrity, and when being connected to IoT devices, it is able to improve transaction efficiency (Kiayias et al., 2017).

- Technological advantages

The information is stored in multiple ledgers database with encryption manipulation and is difficult to be attacked. The consensus mechanisms ensure that information will not be tampered with when all actors agree in traceability process (Watanabe et al., 2015; Liang et al., 2018).

- Improvement of supply chain collaboration and trust

Interoperability and integration of cross-organizational business processes depend on distributed, autonomous and heterogeneous services to execute tasks. Blockchain can enhance trust and collaboration among supply chain partners (Tian et al., 2016). As no-tampering history information can be traced throughout the traceability chain, the information increased quality prediction and evaluation capabilities (Liao et al., 2018; Cartier et al., 2018; Ølnes et al., 2017).

- Reducing economic loss and product waste

Using blockchain-based traceability system can obtain the reliable data of each stage in traceability chain, which contributes to more accurate shelf life of food products leading to the reduced economic loss and food waste (Risius et al., 2017; Mohanta et al., 2018; Korpela et al., 2017).

- Sustainability and transparency of traceability management

Blockchain technology enables end-to-end traceability operations (Kshetri et al., 2018). It can meet the requirements to trace the origin of products from farms to consumers. The traceability information of farming origins, lot numbers, quarantine date, factory and processing details, transportation information, storage data (storage temperature, humidity, gas, time, operator) and shelf-life could be entered into the blockchain at each step of the production process (Thakur et al., 2010; Badia-Melis et al., 2015). As a result, application of blockchain technology can build trust among the stakeholders, which will enable them to inspect the record of whole supply chain. The supply chain participants can track them more comprehensively than ever before. Companies can use the information to provide legal proof for the traceability management of food products, and to prove the authenticity of products. The application of blockchain can make significant contributions to effective sustainability and transparency of traceability management (Galvez et al., 2018; Hong et al., 2018; Chang et al., 2019).

Fig. 8. Benefits of the blockchain-based sustainable traceability management

6.2 Challenges

Although the blockchain can revolutionise the sustainable traceability management practice, many challenges need to be addressed. Based on the literature review, five major challenge areas are identified. Table 4 provides a summary of the challenges that need further investigation.

- Technical challenges

Blockchain technologies challenges related to the scalability, security and stability requirements for the IoT traceability application in the context of global food chain. Design limitations may limit the choice of consensus algorithm, transaction capacity and data accessibility (Zheng et al., 2018; Lin et al., 2017). Future blockchain developments will significantly determine security and integrity for IoT platforms and services.

- Blockchain infrastructure

The security infrastructure of the blockchain faces major challenges. Currently, there are lack of the public-key infrastructure for meeting all the requirements of blockchain-based quality traceability system, such as inter-domain policies and control (Fernández-Caramés & Fraga-Lamas, 2018; Nizamuddin et al., 2019).

- Interoperability and standardization

Interoperability and standardization between ledger types (e.g. public and private ledgers) are important. Blockchain architecture standards need to be developed to allow interoperability between technology solutions for collaborative trust and information protection.

- Social and institutional challenges

Social and institutional challenges mainly include legal and regulations issues. The IoT domain is influenced by a country's laws or regulations on data privacy (Reyna et al., 2018). Currently, blockchain technology does not have a set of clear legal regulations and standards for its implementation. There is a need to introduce legal and regulatory framework to monitor blockchain technology application in the agri-food traceability for compliance.

- System performance

System performance is vital for applying blockchain in sustainable traceability management. One of the challenges is how to ensure the continuous stability and security of blockchain based IoT applications. Thus, a standardized test platform should be evaluated in terms of low-consumption, high latency and storage capacity (Reyna et al., 2018).

Table 4. Challenges of the blockchain-based sustainable traceability management

7. Conclusion and future research

Although blockchain technology has been hailed as a promising solution to address food traceability issues, there is a very limited understanding on its specific characteristics and functionalities for food traceability management, the development and evaluation methods for its implementations, and the benefits and challenges faced by food traceability researchers and practitioners.

To address these research gaps, this paper seeks to answer three key questions: First, how can blockchain technology provide better solutions to address the food traceability concerns in terms of full information transparency and security in food supply chains? This question is addressed by reviewing the blockchain technology characteristics and functionalities and identifying blockchain-based solutions for addressing food traceability issues as presented in section 3. Second, how can blockchain-based IoT traceability system be implemented for food traceability management? This question is addressed by proposing an architecture design framework and a suitability application analysis flowchart for researchers and practitioners to apply blockchain-based traceability systems in section 4 and 5. Third, what are the main benefits and challenges in implementing blockchain technology in managing food traceability? This question is answered by highlighting the benefits and challenges of blockchain-based traceability systems implementation in section 6.

This research provides a timely review on the applications of blockchain technology in sustainable traceability management and makes valuable theoretical and practical contributions by enhancing our understanding and knowledge, providing agenda for further research, and advancing research development and practice on blockchain applications in the sustainable food traceability systems.

However, as a review-based research, this study has certain limitations. The proposed frameworks and guidelines are conceptual based and should be further tested and empirically validated. This limitation provides opportunities for future research. For example, future studies can adapt and evaluate the blockchain-based traceability operational framework, design architecture, analysis flowchart from multi-perspectives in pilot applications. Specific attention should be paid to the hardware deployment, storage capability, transaction speed, and the overall performance of blockchain-based food traceability systems. Future research should also consider how blockchain technology could be applied to enhance the sustainability of various agri-food chains.

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Table 1**Blockchain solutions for addressing the traceability issues**

Traceability issues	How it may be implemented	Feasibility and added value	Reference
How to coordinate transaction activities?	Blockchain technology uses digital distributed databases where blocks are linked to each other in an appropriate linear manner and cannot be tampered with.	Propagate data effectively between the participants using blockchain technology	Galvez et al., 2018 Zyskind & Nathan 2015
How to verify a transaction is fraudulent or invalid?	The Merkle tree is preserved in the block and used to verify the authenticity of the transaction.	Provide the relevant data to the relevant participants	Kshetri et al., 2018
How to link physical flows to information flows?	Connecting blockchain technology applications with precision agriculture, big data, sensors and IoT platforms, connecting to electronic readable labels (identifiers of physical goods) such as RFID, barcode or 2D grid codes and event recording. The recorded event can be included in a blockchain on this product/supply chain	Keep business confidentiality	Khan et al., 2018 Alzahrani et al., 2018 Fernández-Caramés et al., 2018
How to ensure that only legitimate transactions are recorded in the blockchain?	Participants in the supply chain will add a new block of information at the end of the blockchain only they reach consensus on the transaction.	Information reliability	Andoni et al., 2019
How to preserve historic records?	When a block is added to the blockchain, it can no	Improve the information	Thakur et al., 2010 ; Badia-

longer be tampered and security
the transaction
information is
permanently recorded.

Melis et al.,
2015

Table 2

Requirements analysis of the blockchain-based traceability system

Req ID	Traceability Requirements	Contribution of blockchain-based traceability system	Requirements type	References
1	IoT-based data acquisition and transmission	Using blockchain one can control and configure IoT devices	Technical	Cai et al 2014 Caro et al 2018
2	Data security	The whole traceability transaction information and historic actions are recorded and cannot be tampered to achieve data security.	Technical	Yang et al 2016 Lomotey et al 2017
3	Information transparency	Achieved by consensus mechanisms and data opening of blockchain-based technology.	Technical	Yang et al 2016 Galvez et al., 2018
4	Data sharing	Blockchain-based traceability enables distributed data sharing.	Technical	Yang et al 2016
5	Transactions speed	Accelerate transactions of blockchain-enabled IoT traceability system	Performance	Kang et al 2013 Galvez et al., 2018
6	Adaptability	Run stably have well-scalability	Performance	Kim et al., 2017
7	System reliability, stability and scalability	IoT data can remain tamper-proof and distributed in blockchain to improve	Performance	Kang et al 2013 Galvez et al., 2018

8	Deployment	system reliability and high stability and scalability. Be a system easy to operate.	Performance	Celebic et al., 2016
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Table3

Performance dimension in achieving the traceability objectives

Performance dimension	Evaluation criteria	Blockchain's roles	Reference
Technical performance	Efficiency of data transmission	Efficiency of data transmission can be increased by digitizing physical process.	Kshetri 2018
	Trusted authority	Blockchain applies to scenarios where there are no trusted permissions or where current trusted permissions may be dispersed.	Li et al., 2017 Lin et al., 2017
	Data transparency	Blockchain provides a neutral platform in which all participants can see the published data.	Yli-Huumo et al., 2016 Büyükozkan et al., 2018
	Data integrity	Data integrity is a key historical transaction activity created that can be used to track changes in the ownership and processing of physical assets.	Lin et al., 2017 Zheng et al., 2018
	Data immutability	Data on the blockchain cannot be easily changed.	Reyna et al., 2018
System performance	System cost (deploying, invoking, and executing smart contracts)		Kshetri et al., 2017
	Transaction speed	Transaction speed can be increased by DLTs and reducing interactions and communications.	Zhang et al., 2018 Lo et al., 2017
	Dependability	Blockchain can provide a high level of dependability.	Min , 2019
	Risk reduction	Solving the holistic sources of risk.	Lo et al., 2017
	System stability and scalability	System can run stably and can have well- scalability.	Hassan et al., 2019
Flexibility and resilience	Higher level of impact with deeper IoT integration in logistics and supply chain.	Zile et al., 2018 Haddud et al., 2017	

Table 4

Challenges of the blockchain-based sustainable traceability management

Areas	Challenge	Description	Reference
Technology	Vulnerability of smart contracts	It is challenging to make up bugs in deployed smart contracts due to the irreversibility of blockchains.	Alharby et al., 2017 Li et al., 2017
	Consensus algorithm	Permission design and transaction capacity, data accessibility for DLTs and choice of consensus algorithm.	Zheng et al., 2018 Lin et al., 2017
	Data accessibility and integrity for DLTs	Ensuring the security and integrity of input data is very difficult.	Reyna et al., 2018
	Data security	<ul style="list-style-type: none"> ● 51% computation power is not safe. ● High probability of traceability transaction modification for data malleability. 	Khan et al., 2018 Kumar et al., 2018
Infrastructure	Poor infrastructure	<ul style="list-style-type: none"> ● Lack of the public-key infrastructure for appeasing all the requirements of blockchain-based quality traceability system, such as inter-domain policies and control 	Zheng et al., 2018 Shrier et al., 2016
		<ul style="list-style-type: none"> ● The process of integrating all actors in agricultural supply chains onto DLTs ● Lack of digital skills, trust, etc. 	Li et al., 2016
Interoperability and standardization	Failures of interoperability	<ul style="list-style-type: none"> ● The collaboration of all stakeholders to achieve full interoperability ● International standards for collaborative trust 	Kamilaris et al., 2019 Kumar et al., 2018

		and information protection will be needed.	
		<ul style="list-style-type: none"> ● Interoperability between ledger types (e.g. public and private ledgers) 	
	Lack of standardisation and flexibility	Blockchain architecture standards need to be developed to allow interoperability between technology solutions.	Min et al., 2019 Andoni et al., 2019
	Legal	Currently, blockchain does not have a set of general legal regulations and standards to follow.	Risius et al., 2017
Social institutional	Regulatory issues	<ul style="list-style-type: none"> ● Regulatory uncertainties and illegal use of blockchains may occur. ● Regulatory authorities are responsible for setting the rules of consumer data protection. 	Galvez et al., 2018 Kumar et al., 2018
	Communication	Nodes in the blockchain require frequent transmission and data exchange, the capacity of IoT-based devices is much lower than the blockchain requirements.	Reyna et al., 2018 Lin et al., 2017
System performance	Energy consumption	The computation and communication required for blockchain operations is usually energy-intensive.	Dorri et al., 2017 Reyna et al., 2018
	Latency	The high latency of the blockchain is used to ensure consistency of the decentralized blockchain network. For many IoT-	Zheng et al., 2018 Reyna et al., 2018

based applications, the latency that is typically tolerant of Blockchain is unacceptable.

Storage capacity

In BC, each ledger must be stored on its own node.

[Chang et al., 2019](#)
[Reyna et al., 2018](#)

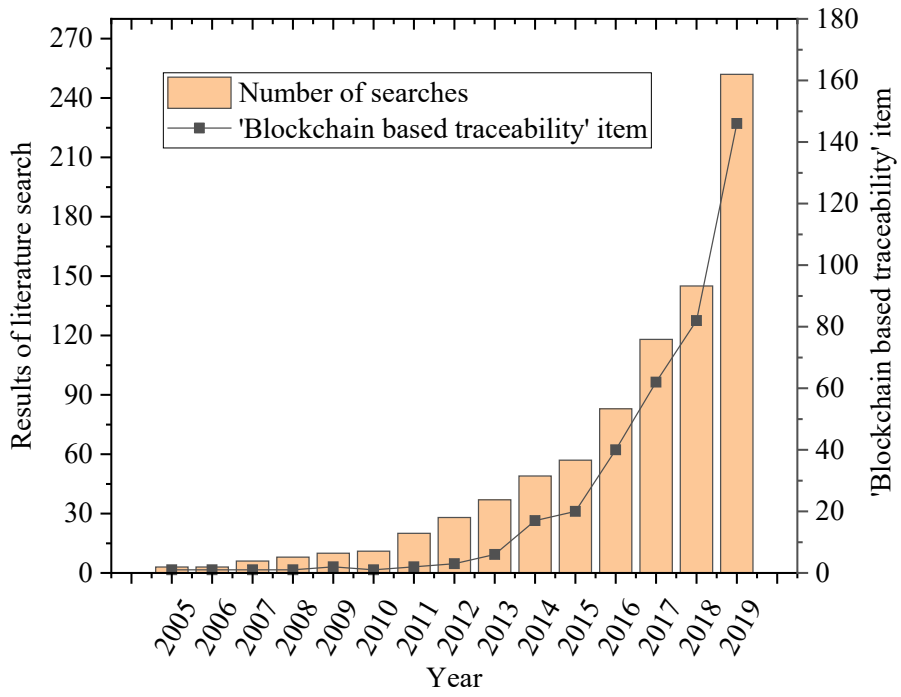


Fig. 1 Results of literature search according to the thematic area identified

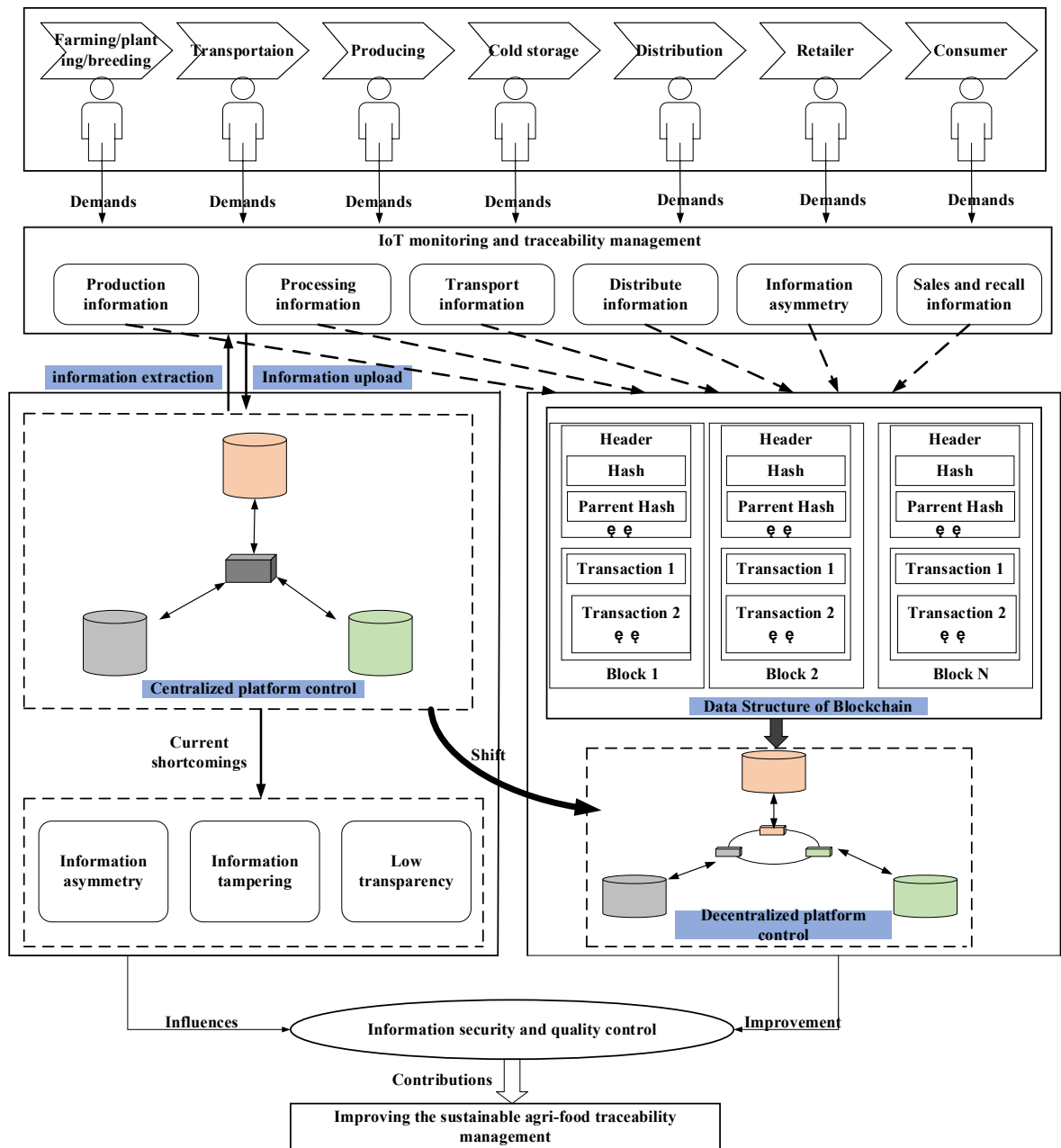


Fig. 2. The operational framework of blockchain-based traceability

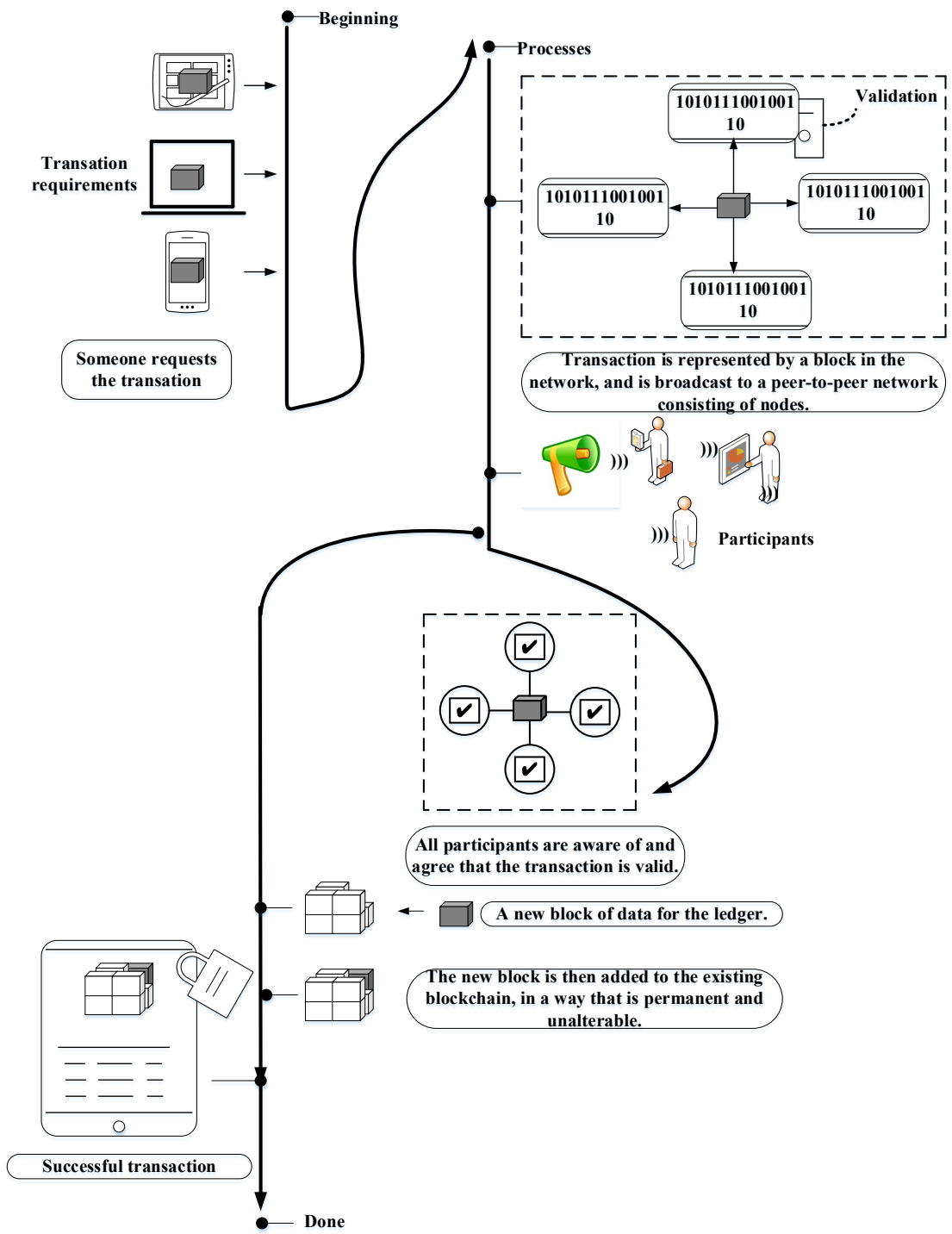


Fig. 3. Operational mechanism of blockchain technology

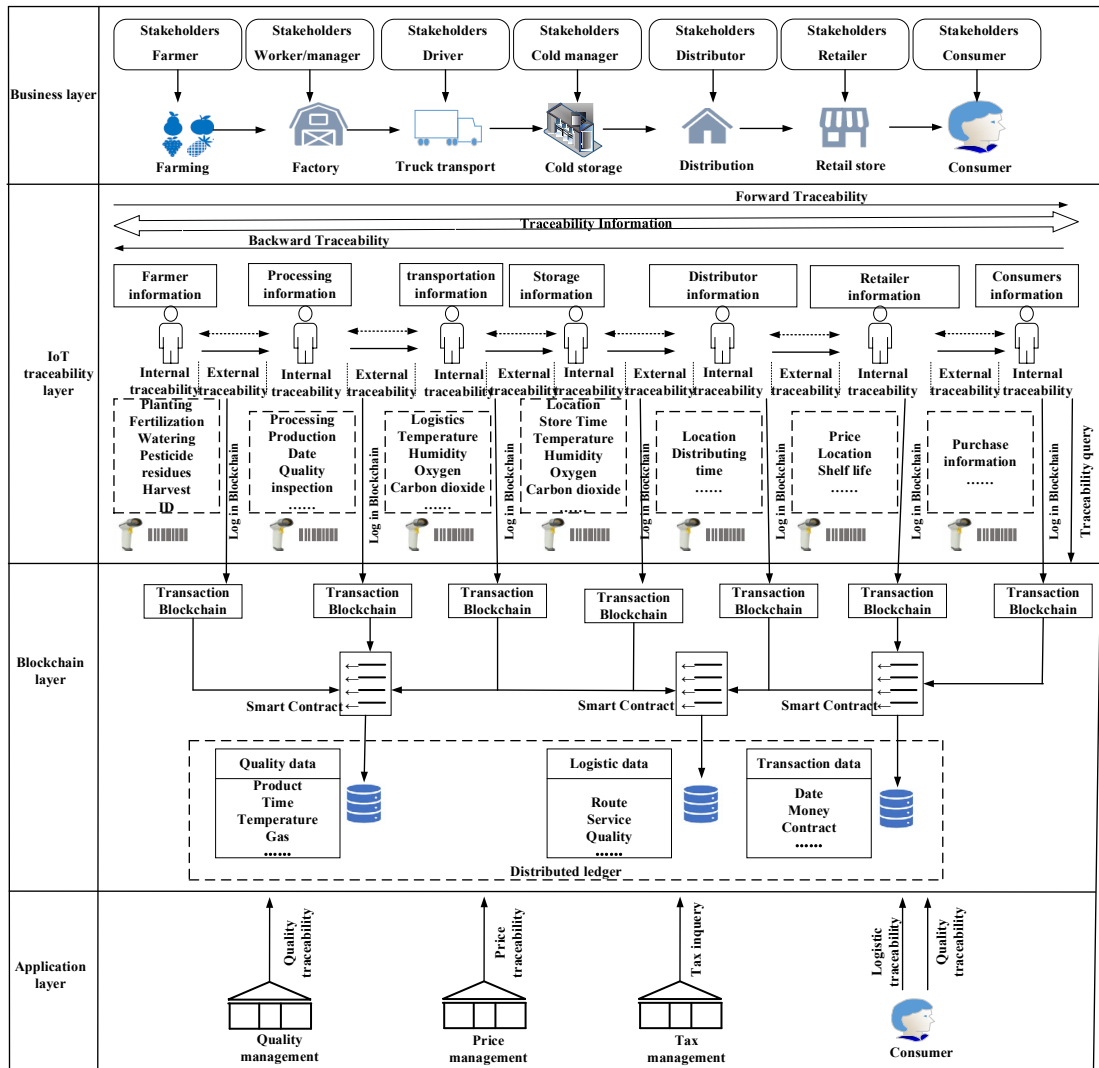


Fig. 4. Architecture of blockchain-based food traceability system

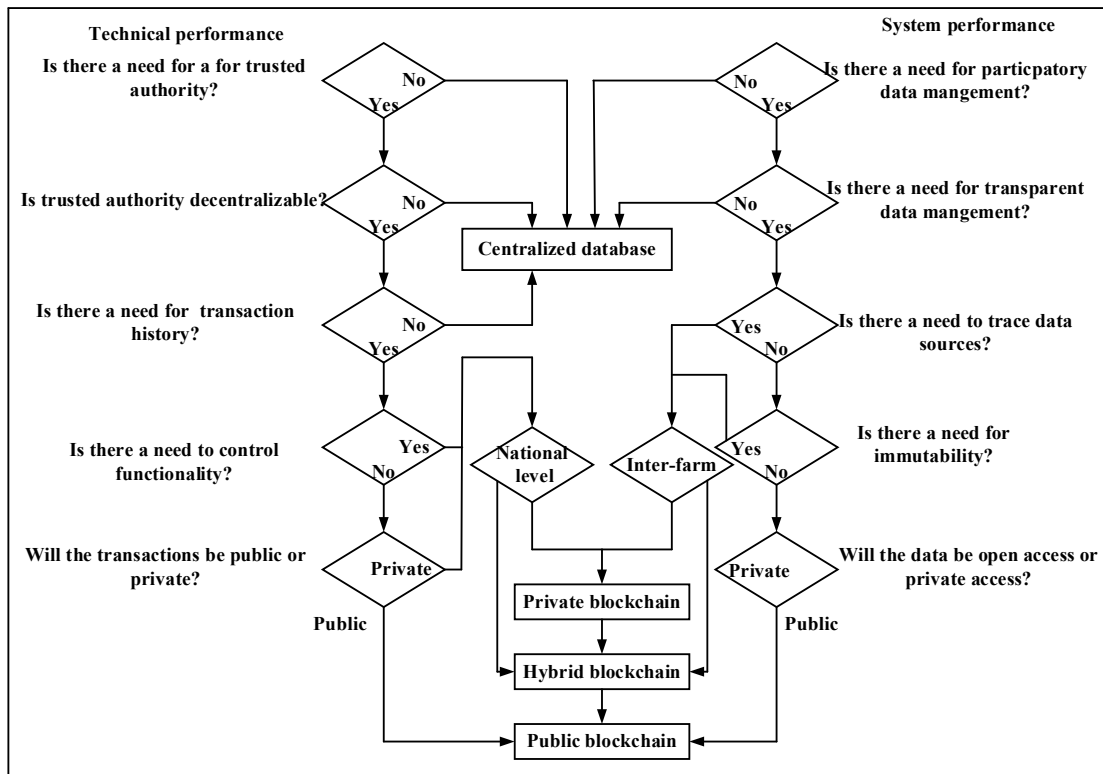


Fig. 5. A flowchart of suitability and sustainability application analysis for blockchain- based traceability system

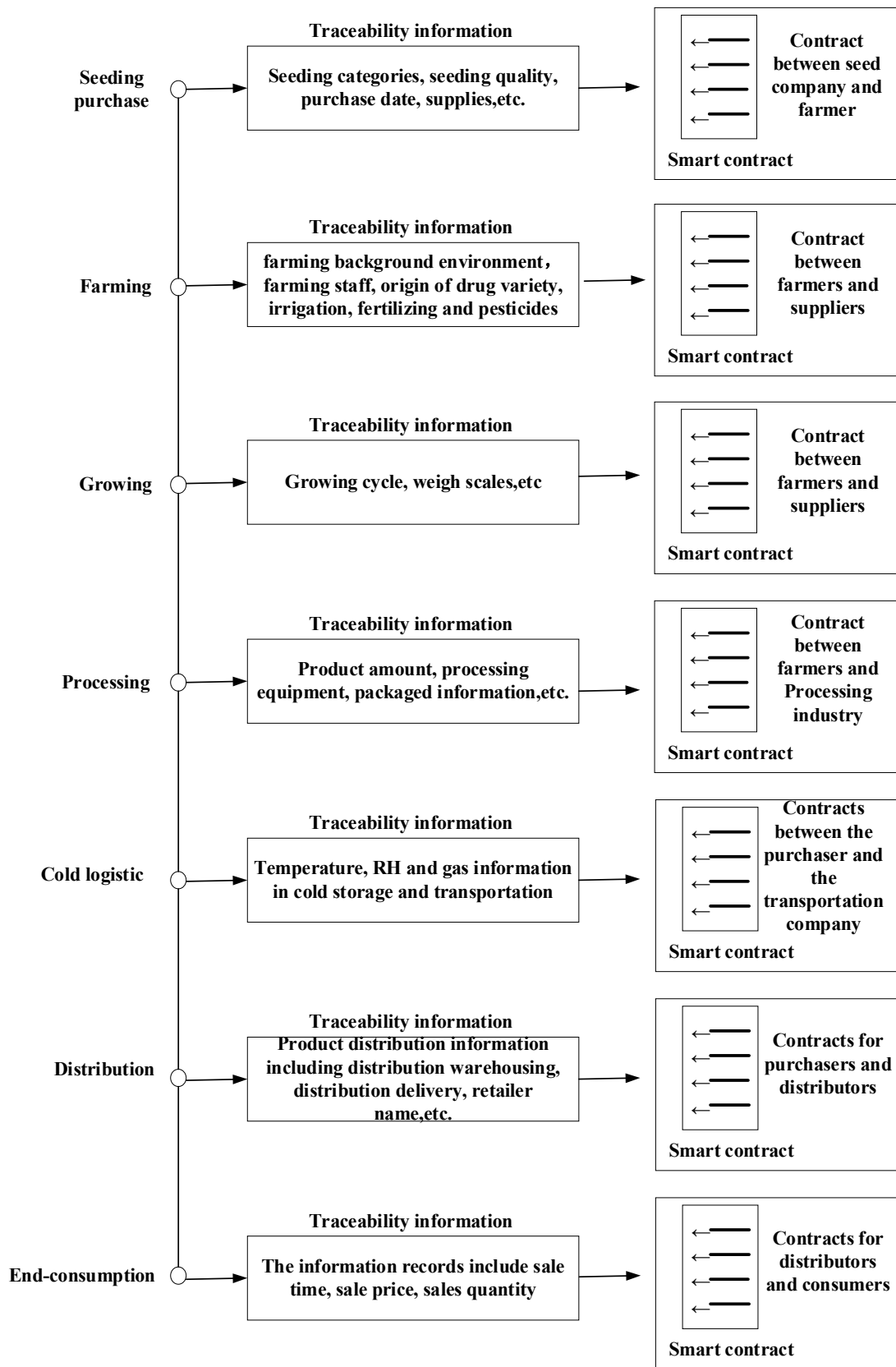


Fig. 6. The blockchain-based traceability process of plant food production

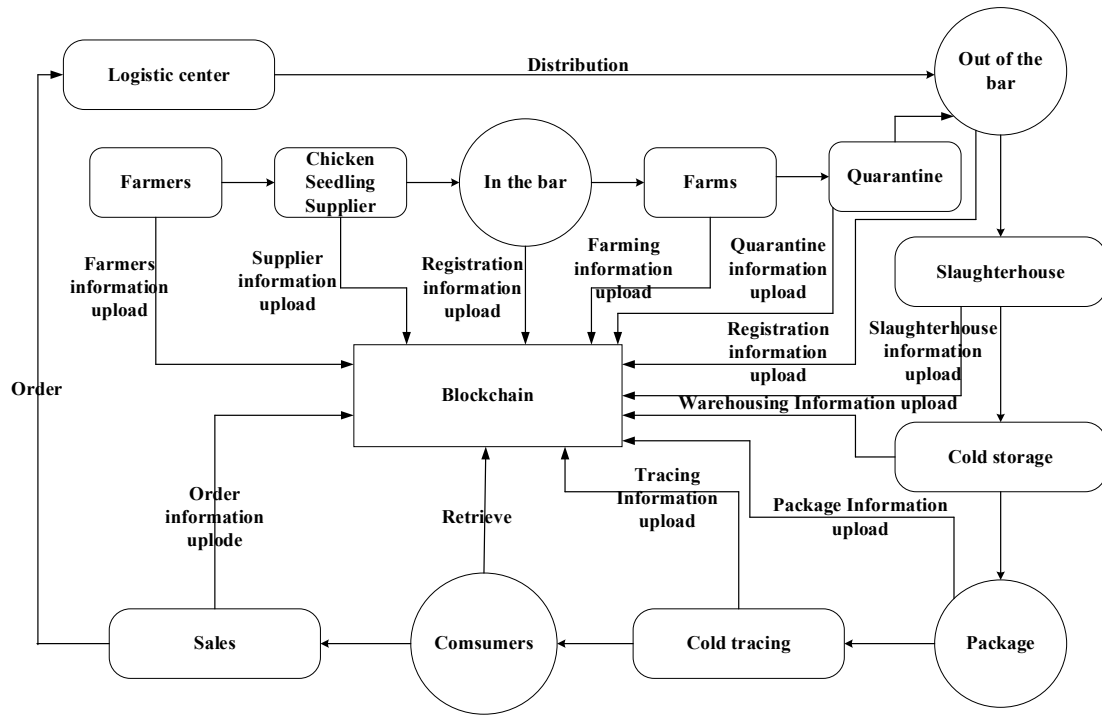


Fig.7. Blockchain-based traceability process of chicken poultry

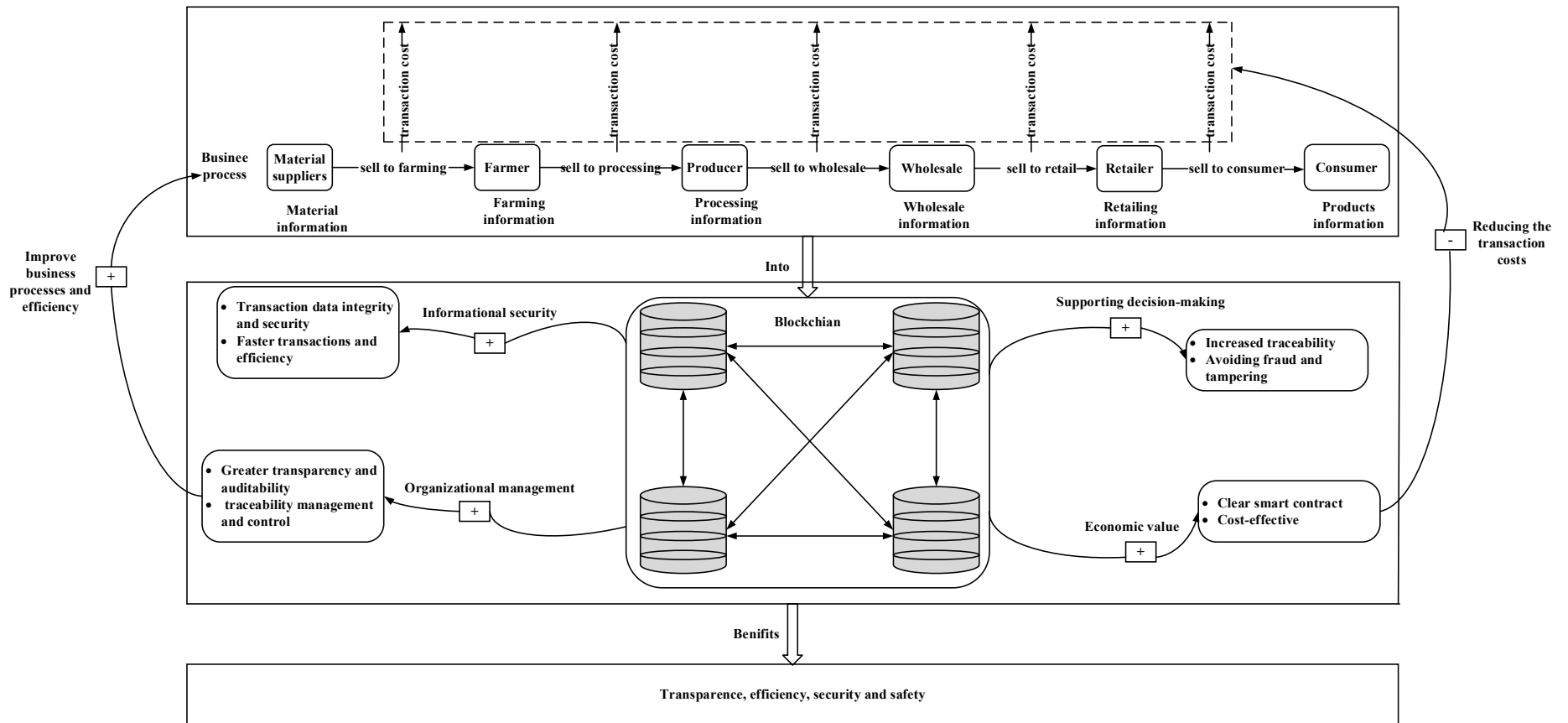


Fig. 8. Benefits of the blockchain-based sustainable traceability management