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Review

Blockchain Applications in Agriculture: A Scoping Review

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Abstract: Blockchain is a distributed, immutable ledger technology initially developed to secure cryptocurrency transactions. Following its revolutionary use in cryptocurrencies, blockchain solutions are now being proposed to address various problems in different domains and is currently one of the most "disruptive" technologies. This paper presents a scoping review of the scientific literature for exploring the current research area of blockchain applications in the agricultural sector. The aim is to identify the service areas of agriculture where blockchain is used, the blockchain technology used, the data stored in it, its combination with external databases, the reason it is used, for which products, as well as the level of maturity of the respective approaches. The study follows the PRISMA-ScR methodology. The purpose of conducting the scoping review is to identify the evidence of this field and clarify the key concepts. The literature search was conducted in April 2021 using Scopus and Google Scholar, and a systematic selection process identified 104 research articles for detailed study. Our findings show that in the field, although still in the early stages, with the majority of studies in the design phase, several experiments have been made, so a significant percentage of the work is in the implementation or piloting phase. Finally, our research shows that the use of blockchain in this domain mainly concerns the integrity of agricultural production records, the monitoring of production steps, and the monitoring of products. However, other varied and remarkable blockchain applications include incentive mechanisms, circular economy, data privacy, product certification, and reputation systems.

Keywords: Blockchain; Distributed Ledger Technology; Agriculture; Scoping Review; PRISMA-ScR

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1. Introduction

At the dawn of 21st century, the agricultural industry, which is still rapidly growing, represents a turnover of 3.5 trillion dollars [1], but also faces many challenges. The most important of which is the assurance of safe, nutritious, and sufficient food for everyone, as defined by the United Nations 2030 agenda for sustainable development [2].

According to product safety regulations, everyone must follow specific standards, such as GATT and WTO [3,4]. However, there is no standard global agricultural protocol shared among agriculture participants, only regional regulations, which leads to misunderstandings and increases the risks to consumer safety. The agriculture supply chain involves many intermediaries, such as farmers, distributors, retailers, and final sellers. Those parties use private databases and documents to store critical information about the origin and safety of products, to which only regulators have access, making them vulnerable to breach or loss of data [5,6]. Therefore, the trust between them is an essential part of reducing the risk of the supply chain safety [7].

The importance of all the above becomes more understandable if we consider that several hazards can cause physical, biological, or chemical contamination from production to our plate throughout the food supply chain. A shocking example of this is the 2006 incident in the United States where a batch of spinach containing E. Coli was distributed in 26 states and infected 205 people, 3 of whom died [8]. The remarkable thing was that it took more than three weeks to find out where the infection came from, while the consequences on the market were incalculable. Consequently, traceability in the production line has a critical role [6]. Of equal importance is the monitoring, recording, and control of essential parameters that cover the entire product's life cycle [9]. In addition, in the last decades, consumers have begun to be interested in the origin, certification, and quality of products in terms of the importance and attention given when making market decisions [10]. Another major challenge nowadays is food waste due to the expiration of products. For example, the European Union discards about one-third of the outcomes, which is equivalent to 88 million tonnes [11]. Finally, an open-ended issue over time is the equal pay for producers and the fair trade in products [12].

In short, in agriculture, there are still open issues regarding product traceability and monitoring, trust among supply chain parties, equal pay for producers, production sustainability, and other issues. Thus, blockchain could be a potential technology that can treat most of these issues, with an emphasis on providing greater security to existing or new solutions in this direction.

1.1. Blockchain Technology

According to Manyika [13], the agricultural sector is one of the industries with the least integration of digital technologies. Nevertheless, the use of information and communications technologies, such as blockchain, deep learning and the Internet of Things (IoT), promise to bring digitization to agriculture and solve the above problems [14]. Especially, blockchain, due to its decentralized nature and management, could potentially provide solutions to ensure the integrity and immutability of transactions.

The first distributed blockchain technology was described as a fundamental component of the Bitcoin cryptocurrency [15]. This idea proved to be a success and managed to change the model of central management. The inherent features of blockchain architecture and design provide properties such as transparency, decentralisation, accessibility, autonomy and immutability. In its original application in Bitcoin, the blockchain allowed users with only a predefined function, which was to exchange cryptocurrencies. However, that changed drastically in 2015 with the creation of Ethereum [16]. Ethereum is a blockchain system that allows anyone to build applications that will run on it. These decentralized applications are called DApps, based on smart contracts and written in high-level programming languages.

Through smart contracts, decentralized structures can enable transactions between organizations without a central authority to be in control. Blockchain introduces the idea of "Decentralized Autonomous Organizations" (DAOs), where organizations can form entities where no central authority will be needed, but everything will be regulated by specific rules that they will have agreed upon and will be imposed by smart contracts [17,18].

The proper functioning of these DAO entities as well as the blockchain is based on consensus algorithms. The consensus protocol defines how different nodes agree on a result that will be appended to the next block [19]. Ensures security, data accuracy and that all members follow the rules that have been set. The consensus algorithm differs depending on the type of blockchain. Public and private blockchain use different consensus algorithms based on their requirements. The different need for trust between these types of networks defines the consensus algorithm. In public blockchains where anyone can participate, there is no trust in the network, and therefore heavier consensus algorithms are needed to ensure network integrity. Consequently, variants of Proof of Work (PoW) or Proof of Stake (PoS) algorithms are used that offer fault tolerance and security, but a slow transaction confirmation rate [20]. On the contrary in private blockchains, all participants have a known identity and role, so they are governed by trust and more efficient consent algorithms can be used in terms of transaction speed. The most common are Practical Byzantine Fault-Tolerance (PBFT) and Raft consensus algorithm [21]. Finally, the need for blockchain in particular application domains has led to the recent trend of creating application-specific consensus algorithms suitable for specific tasks (e.g., IoT, supply chain, and trading) [20].

1.2. Blockchain Technology in Agriculture

Following this revolutionary idea, the prospects of blockchain evolved rapidly, with blockchain being used in areas other than cryptocurrencies, and smart contracts [22] playing a central role in creating enormous potential. Blockchain can increase transparency and accountability in supply chain networks and help detect counterfeit products easily, reduce intermediaries, and facilitate product traceability [23]. Such characteristics could potentially benefit the agricultural sector. Indeed, many of the blockchain advantages we mentioned are already provided in existing conventional solutions and often more efficiently. However, blockchain is an infrastructure that can additionally offer data immutability as well as through its inherent features to help build confidence between untrusted parties [24].

This trust is essential given the nature of the supply chain and the confidence that is achieved between organizations can increase the use of digital technologies [25]. The agriculture supply chain consists of many different parties (e.g., farmers and resellers) that are usually not located in the same geographical area and deal with natural products or services without knowing all the other partners. This complexity of the supply chain can be problematic and an obstacle to cooperation between the parties [26]. Blockchain can offer a possible solution to this by improving the level of trust between the participants of the supply chain [27,28]. Also, through the blockchain, there can be transparency throughout the agricultural chain, which will help build trust indirectly [29].

Additionally, the Food and Agriculture Organization (FAO) of the United Nations has recognized the importance of the blockchain in the agricultural sector [30]. Because of all these potential advantages, companies have already proposed blockchain-based solutions [31]. These blockchain applications in agriculture can provide various solutions, such as:

- Product traceability and logging (e.g., IBM Food Trust [32], Ambrosus (ambrosus.io), and TE-FOOD (te-food.com)): Consumers and regulators can ensure the origin of the products. Also, they can store product information from IoT devices and sensors.
- Ensuring trust between participants (e.g., TrustChain [28]): Blockchain can help supply chain participants trust each other through the transparency and immutability it can offer.
- Providing equal pay to producers (e.g., FairChain (fairchain.org)): Blockchain can be used to reduce intermediaries and distribute profits transparently to producers.
- Product insurance and claiming compensation (e.g., Etherisc (etherisc.com)): Smart contracts can replace insurance documents and schedule insurance activation according to IoT sensors. All the transactions are transparent and visible from the other parties.

Even though various aspects of blockchain use in agricultural production have been clarified, some issues still remain open. For the full adoption of blockchain in the agricultural sector, a number of technological barriers must first be addressed, such as blockchain scalability [33], the cost and performance of blockchain data stores [34], and privacy issues related to blockchain usage [35]. As the agricultural sector includes many different autonomous parties, another issue is the management of multi-blockchains [36] for the interoperability between organizations. Finally, aspects of blockchain use in the agricultural sector have not been identified in detail, such as which agricultural service areas the blockchain can be used for, what is the reason for its use, and what type of data is stored in-chain and off-chain.

The focus of our study is to analyze such aspects of blockchain technology in the agricultural sector as presented in the scientific literature. Through the scoping review that we conducted, we try to answer a variety of research questions about the use of blockchain in agriculture, and to identify existing knowledge gaps. Furthermore, this work may lead to more detailed systematic reviews of these technologies in agricultural sub-sectors.

1.3. Related Work

Although there are various reviews regarding the use of blockchain in agriculture, only one is the most extensive, Kamilaris *et al.* [37], which includes 49 papers, while in 2021 the same main author, Kamilaris *et al.* [38], published a book chapter which includes this time 80 papers. The rest of the reviews [e.g., 39–45] include a smaller number of papers either due to more specific questions or mainly due to the early stage of technology when conducting their research. This is mainly due to the recent explosion of blockchain use and the corresponding increase of the related scientific literature. There is also a difference in the exact focus area of each review paper, with some reviews answering questions about blockchain use in food [40], others about blockchain in agriculture and the food supply chain [37], or just about blockchain in agriculture [42,44,45].

The present work, in relation to previous related work, is novel in several aspects. First, our research is the most comprehensive literature review that has been done so far, including a total of 104 research papers. Second, our research area is focused not only on blockchain, but also on distributed ledgers technologies in agriculture. Thirdly, we apply the widely used PRISMA-ScR [46] methodology for systematic scoping reviews. To the best of our knowledge, this is the first systematic literature search in this field following a formal methodology. Finally, in our research, we examine a wider range of research questions, some of which have not been mentioned in the past in the existing literature. For example, we answer questions about application development beyond the blockchain technology used, the service area, the maturity level, the country, or the product to which the application refers. Such were the data stored on-chain/off-chain (and also the off-chain technology used), the reason for using the blockchain, and the type of blockchain.

1.4. Contribution

Our main contributions can be summarized as follows:

- We provide a comprehensive scoping review of blockchain applications in agriculture.
- We answer research questions that have not been addressed in previous work, such as data on-chain/off-chain, off-chain technologies used, type of blockchain, and the reason for using blockchain. In addition, we set research questions about the exact blockchain technology, the maturity level, the provided service area, the agricultural products, and the country.
- We use a formal methodology as defined by Prisma-ScR. This scoping review is the first in this multidisciplinary field to the best of our knowledge. This type of review is the most appropriate knowledge synthesis approach for systematically mapping concepts that support a broad research area, such as the blockchain in agriculture.
- We analyze our findings based on nine research questions, visualize the results, and provide a focused discussion for each research question, as defined by our scoping review methodology.

1.5. Outline

The remainder of the paper is organized as follows: Section 2 describes our research questions, defines the protocol and the method that we use, and also explains the details of the features we gather. Section 3 presents and visualizes the results of our scoping review. Section 4 summarizes our main findings, and discusses our evidence and the limitations of our study. Finally, Section 5 concludes this scoping review paper.

2. Methods

2.1. Goal and Research Questions

Our scoping review is conducted to map the research done in this area systematically and to identify any existing gaps in knowledge to which the scientific community can contribute. As a result, the following research questions are formulated:

RQ1. What service areas have been addressed in the current use of blockchain technology in agriculture?
RQ2. What is the maturity level of blockchain applications in the agricultural sector?
RQ3. Which products are primarily used in agricultural blockchain applications?
RQ4. For which country were the solutions created or implemented?

RQ5. What kind of blockchain technology is used?
RQ6. What type of blockchain is used?
RQ7. What types of data are stored in blockchain in the agricultural applications?
RQ8. Is there data stored off-chain and linked to the blockchain?
RQ9. What are the main reasons for using blockchain technology in the agricultural sector?

2.2. Research Protocol

The present study follows the scoping review methodology, the most appropriate knowledge synthesis approach for systematically mapping concepts that support a wide research area and categorizing this knowledge. In contrast to the systematic review [47, 48], research questions do not focus on specific parameters. They also do not define quality filters, as is the case in a systematic review, which is not easy to happen in an interdisciplinary field such as the one we are studying. These make the scoping review suitable in areas where more specializations coexist, as in our case. The composition of the data is also grouped, and we do not refer to each one individually, something that would not be possible with the volume of research we have. Grouping also helps categorize the findings that we need to draw general conclusions and find gaps in the literature, which is the purpose of the scoping review.

The scoping review protocol of this study was developed using the PRISMA methodology [49] and, in particular, the PRISMA-ScR, which is an extension for scoping reviews [46]. PRISMA methodology is the most used and cited framework for systematic reviews and meta-analyses, and its extension is used to synthesize data and evaluate the scope of the literature. A summary of the protocol procedure is demonstrated step by step in the following subsections.

2.3. Eligibility Criteria

Prerequisites for including the papers in the review were the reference to certain aspects of blockchain technology that applied to a problem in the agricultural sector. The papers must be peer-reviewed journal articles or conference papers, published up to the day the queries were searched, written in English, and refer to our question: the use of blockchain in agricultural production or related derivatives. Papers were excluded if they did not fit into the study's conceptual framework, especially if they were mentioned in reviews and position papers or blockchain applications not directly related to agriculture. Also, the papers are excluded if they do not have a scientific background, are demo, or are published without peer review. In addition, we have not used grey literature. Finally, we have excluded papers that refer to blockchain but do not explicitly mention its use, e.g., a machine learning system that claims to receive agricultural information from the blockchain without stating its structure or the data stored on it.

2.4. Information Sources and Search

To identify potentially relevant publications, the following online bibliographic databases were searched: *Scopus* and *Google Scholar*. The Scopus database was used because it contains the most important digital libraries, such as *Elsevier*, *Springer*, *ACM*, and *IEEE*. It also provides advanced search and is easy to export. The following query was performed on April 9th, 2021 in Scopus:

```
TITLE-ABS-KEY ((agriculture OR agricultural) AND (blockchain OR
                 “distributed ledger”))
```

Google Scholar was also used, in addition, so that we do not omit significant papers from the blockchain application in agriculture. The searches were done on April 14th, 2021 and the following queries were used:

```
allintitle:  agriculture blockchain
allintitle:  agriculture ‘‘Distributed Ledger’’
allintitle:  agricultural blockchain
allintitle:  agricultural ‘‘Distributed Ledger’’
```

Results from Scopus were retrieved using the provided export function in BibTeX format. In Google Scholar, we used the Publish and Perish tool to search for and retrieve articles in the same format. The BibTeX files were then converted to CSV using the open-source bibliography reference manager Zotero [50]. The citation details for all retrieved papers were eventually compiled into a single Microsoft Excel file for further study.

2.5. Selection of Sources

In order to achieve the best coherence among the reviewers, we defined the data we needed to find an answer based on our research questions we asked and created the appropriate framework for extracting this data from the papers, so that there is a unified approach. We also set the exclusion criteria as they refer to the eligibility criteria section. First, we separated the duplicate papers that appeared. Then, the authors of this paper independently examined the title and abstract of all publications and excluded publications according to the criteria set. All papers that did not contain an abstract in English, were not scientific or just discussion papers were excluded. We also excluded the review papers and kept them for further analysis in order to compare them with our results. Instead, in this step, we included papers for further study if any of the above could not be understood from the title and abstract. The reviewers discussed the papers which they excluded and agreed on a consolidated list of publications. The four reviewers then independently reviewed the full text of all retained list of publications. Everyone extracted the data we set. After this step, we resolved the disagreements over the data we extracted. If there was no consensus, discussions were held with other reviewers.

2.6. Data Charting and Data Items

A data charting form was developed jointly by the authors to determine which variables to export. Then, they independently charted the data and discussed the results. Minor discrepancies were resolved again by discussion and a unified data chart was constructed (available upon request).

For each paper included in the list after the first screening, the following data items were exported:

- *Year of publication:* as stated in the search engines export results.
- *Source type:* publication types which we categorized into a) conference papers, b) journal articles.
- *Publisher:* as stated in the search engines export results.

For each research paper that was finally included in the scoping review, additional data items where extracted in order to categorize the paper. The authors studied the papers to extract mapping keywords related to the scoping review research questions. During this process, we constructed a classification scheme based on the identified data items. The papers were classified into the specified categories. Finally, the following additional data items were exported:

- *Service area:* the specific service area considered in the publication, e.g., monitoring, management, certification, etc.
- *Maturity level:* using the following scale (a) Conceptual: a proposal idea with a specific system architecture; (b) Simulation: an application of blockchain was created using a simulate software or framework; (c) Partial Experimental: partial experiments have been performed but not on the blockchain; (d) Experimental: extensive experiments were performed without creating a complete system with front-end, usually to find cost and time, but also other aspects of the blockchain; (e) Proof of Concept: a proof-of-concept (POC) approach tests whether a particular concept is feasible from a technical

point of view. The POC approach requires a simple end goal, and demonstrates whether that goal can be achieved or not. It usually has a front-end; (f) Evaluation: system testing and evaluation with real or not data; (g) Prototype: an initial small-scale implementation that is used to prove the viability of a project idea. A prototype attempts to test the critical aspects of the entire system; and (h) Piloting: a pilot test validates a fully functional product that is offered to a portion of your target users. It has a complete ready-make system, and is tested for a subset of our audience.

- *Agriculture product:* information about the agricultural products or goods in which the blockchain application is used.
- *Country:* the country, if mentioned, for which the application was created (to solve specific difficulties that prevailed) or where it was used and evaluated.
- *Blockchain technology:* the specific blockchain infrastructure (if any) used or proposed in a provided solution, e.g., Ethereum, Hyperledger Fabric, etc.
- *Blockchain type:* the classic categorization into public, private and consortium blockchain or even the NIST categorization [51] into permissioned and permissionless blockchain leads to the problem that it is not clear whether they refer to data reading or the consensus mechanism. The solution to this problem is the dual name proposed by the European Commission [52] and we follow it in this scoping review. More specifically, this categorization is as follows (a) Public Permissionless: in this case both the transaction data and the participation in the consensus algorithm are accessible to all those who participate in the network (such as Ethereum and Bitcoin); (b) Public Permissioned: unlike public permissionless blockchains, while the transaction data is open to everyone, the transaction validation involves specific users who have been authorized (such as Ripple and private versions of Ethereum); (c) Private Permissioned: such blockchain networks restrict to specific users both access to data and participation in the consensus mechanism (such as Hyperledger Fabric); and (d) Private Permissionless: these blockchain networks are not widely known. While the data is accessible only to authorized users, the consensus mechanism is made by all participants in the network.
- *Data on blockchain:* the specific data stored in the blockchain according to the publications.
- *Off-chain data:* the data stored outside the blockchain using other technological solutions. We also mention, in addition to the data, the specific technology (if any) used, such as IPFS, Swarm, SQL databases, etc.
- *Reason for using blockchain:* it describes to what end blockchain technology is exploited in each solution, such as logging, integrity, transparency, access control, etc.

2.7. Synthesis of Results

After the first screening, we analyzed the overall results to present an overview of the existing literature on blockchain applications in the agricultural sector. We focused on literature presenting demographic data of the solutions (year, source type, service area, maturity level, agriculture product, and country) and the data related to blockchain (blockchain technology, blockchain type, data on blockchain, off-chain data, and reason for using blockchain). The individual characteristics of each publication are presented in tabular form. We tried to group the data items as much as possible. We have also computed and analyzed in various diagrams the results of the scoping review. Finally, we summarize and discuss the finding for each of our research questions.

3. Results

3.1. Selection of Evidence Sources

A total of 636 abstracts were retrieved (398 from Scopus and 238 from Google Scholar). First, we remove 118 duplicate records. After the first screening, 387 of the remaining 518 papers were excluded: 110 were not related to our research scope, 30 were not in English, 44 were introductory materials from conferences proceedings, 48 were not scientific papers, 55 were review papers, 70 were discussion papers, and 35 were papers that could not be accessed. Eventually, we came up with 131 unique papers identified for complete paper analysis. During the second screening, 22 papers were excluded as not relevant to blockchain applications in the agriculture sector. The remaining 104 research papers were included in the scoping review. The source selection process is shown in Figure 1. Overall, 16.35% of the retrieved papers were relevant to the study's topic and were included in this scoping review.

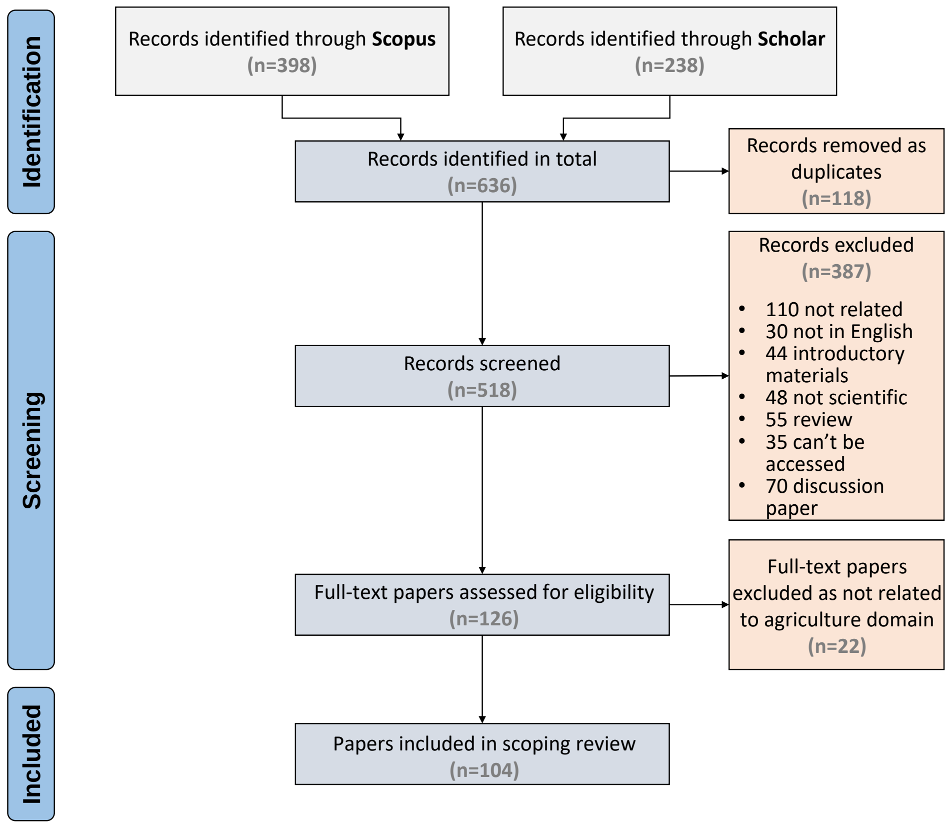


Figure 1. Source selection process from bibliographic search engines.

Figure 2 shows the yearly distribution of publications that were retrieved by search engines (after duplicate removal) and the final papers included in our scoping review. As we found out, there is an increasing trend in blockchain research in the agricultural sector. All papers, in our review, have been published from 2017 onward: 3 papers (3%) published in 2017, 7 papers (7%) published in 2018, 28 papers (27%) published in 2019, 47 papers (45%) published in 2020, and 19 papers (18%) published until April of 2021.

Figure 3 presents the number of papers per publisher that was finally included in our scoping review. IEEE holds the highest number of papers, corresponding to the 42% (44 papers) of all relevant papers. Other publishers that appear very often in our papers collection are Elsevier 13% (13 papers), Spring 13% (13 papers), and MDPI 11% (11 papers). In addition, few works have been published in IOP 5% (5 papers) and ACM 4% (4 papers). Finally, there are 14 papers (13%) that have been published in other publishers.

Further analysis of 104 papers related to blockchain application in the agriculture domain shows that 63 (61%) publications are full conference papers and 41 (39%) are journal papers (Figure 4). Journal papers are scattered in 25 different journals; only eight journal titles have published more than one paper on blockchain applications in agriculture. The journals with the most published papers are: IEEE Access (6 papers), Sustainability (5 papers), Computers and Electronics in Agriculture (3 papers). There are also five more journals with more than one paper in our review: Journal of Cleaner Production, Future Generation Computer Systems, Sensors, Journal of Computers, and International Journal

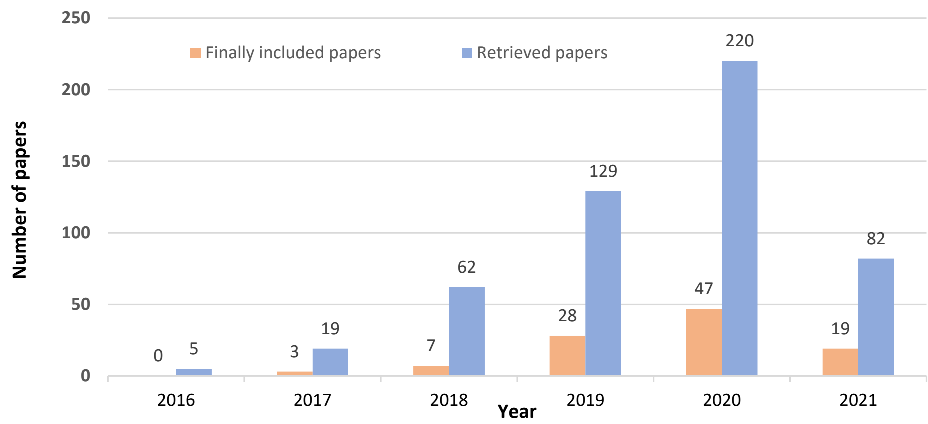


Figure 2. Yearly distribution of papers retrieved (blue) and finally included (orange) in our scoping review.

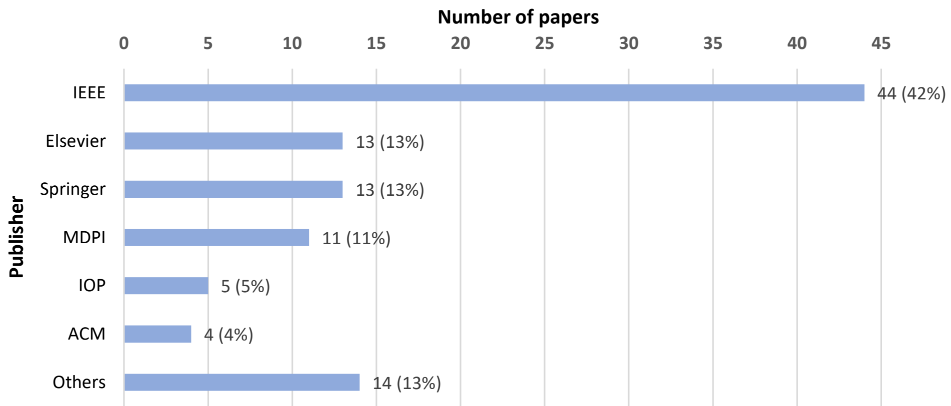


Figure 3. Distribution of papers per publisher related to blockchain applications in the agriculture domain.

of Advanced Computer Science and Applications. Conference papers are published in 59 different conference proceedings; only four conference proceedings titles published more than one paper included in this scoping review, namely IEEE ICBC, IEEE ICCCSP, ITIA, and IEEE ISPA/BDCloud /SocialCom/SustainCom (2 papers).

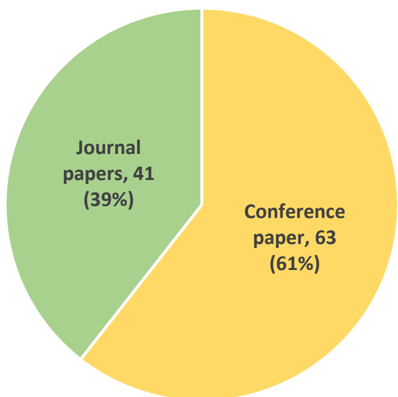


Figure 4. Number of papers from different types of publication.

3.2. Characteristics of Sources and Synthesis of Results

The characteristics and data chart for each of the 104 research papers included in the scoping review are presented in Table 1.

The service areas (RQ1) addressed in our findings on the current use of blockchain technology in agriculture are shown in Figure 5. The majority of papers address the application of blockchain technology for management purposes (75%) and the monitoring of products (55%), which, as we expected, are the most common uses. The next favorite provided service is the certification of products (8%). Other service areas that are addressed include access control devices (4%), producers' reputation (4%), products' trading (4%), auctions (3%), reward systems (3%), and for data sharing reasons (2%).

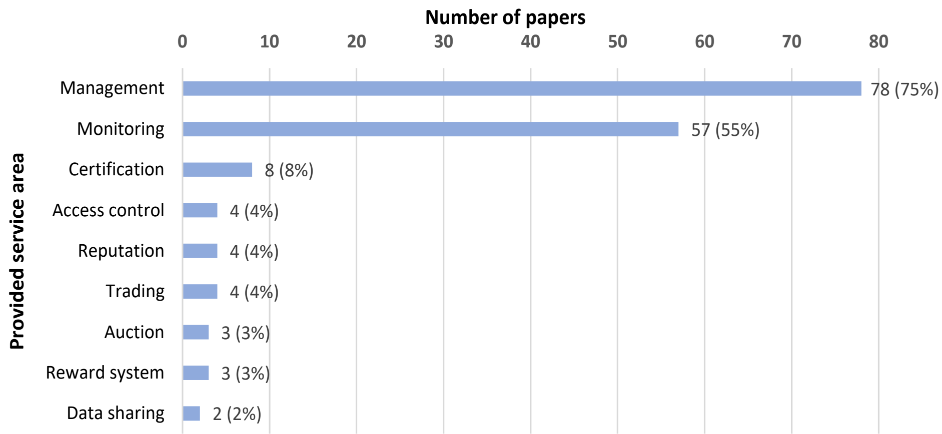


Figure 5. Service areas addressed in the papers included in our scoping review.

Overall, blockchain applications in the agricultural sector are at a relatively early stage of maturity (RQ2), as we found. More than half of the papers propose a solution that has not been implemented yet, as shown in Figure 6. Most of the research works (39%) are at a conceptual level, 7% are simulations, and 9% are partially experimental. On the contrary, 19 papers (18%) at the experimental level perform various experiments in blockchain technology, and 14 papers (13%) are at the proof-of-concept level. Only 14 research papers are at a high level of maturity, 7 of them (7%) are at the evaluation level using existing datasets to test their proposals, 3 papers (3%) have created a prototype implementation, and finally, 4 solutions (4%) are in a pilot phase.

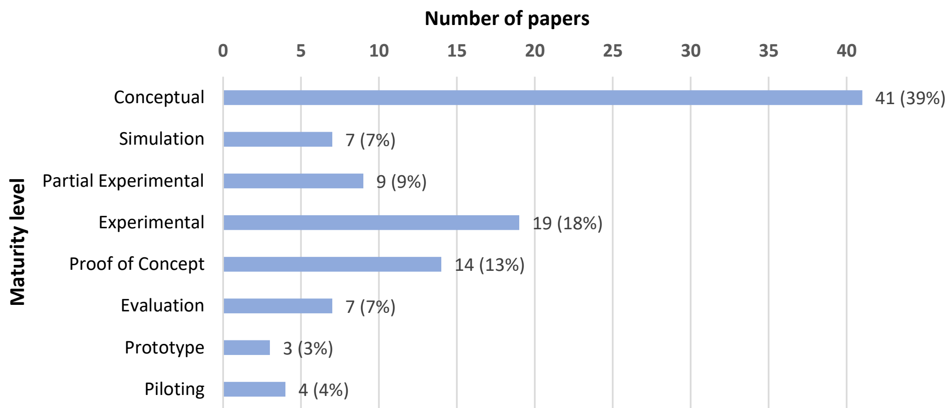


Figure 6. Maturity of the research presented in the papers included in our scoping review.

Figure 7 depicts the classification of research papers by the agricultural sector and products (RQ3) primarily used in agricultural blockchain applications. Most papers (39%) refer to the farming sector, while a significantly smaller percentage refers to the livestock sector (14%). Our findings show that many research solutions (38%) do not explicitly mention either the product or a specific sector. There is also a small percentage (9%) that refers to essential goods for the agricultural process. Furthermore, the products on which the solutions are focused are quite different from each other. The most common are crops (15%) and organic foods (4%), followed by grain, beef, and milk with 3%. There are also solutions that belong to the 2% and refer to corn, soybean, oil, wine, chickens, and cows. Other products only referred to one solution are: citrus, tea, pumpkin, etc. Finally, we observe that there are solutions that do not refer directly to the agricultural sector but indirectly, such as water irrigation (6%), photovoltaics (2%), and wastes (1%).

Figure 7. Agriculture sector and products addressed in the papers included in our scoping review.

Figure 8 illustrates the geographical location for which the proposed solutions were created or implemented. Only 36% of the total solutions have been made for a specific geographical area. More than half of the proposed solutions referred to the Asian continent. More precisely, 11 papers (30%) focus on China, 5 papers (14%) on India, and 2 papers (5%) on Vietnam and Pakistan. The remaining 17 blockchain solutions in the agricultural sector (46%) are scattered in 16 countries; only Spain referred to more than one solution, specifically in 2 papers (5%).

Analysis of each source identified more specific attributes about the blockchain technology framework (if any) used, the blockchain type utilized in the applications, the specific data stored on-chain and off-chain, and reasons for using blockchain; a summary of data charted is shown in Table 2.

Figure 9 shows the various blockchain technology frameworks (RQ5) that are considered by the proposed solutions. The most used blockchain technology is Ethereum (35%) and Hyperledger Fabric (20%). On the other hand, a large part of the solutions does not mention any specific blockchain technology (32%), while some have created a custom blockchain network (9%) which is either based on an existing framework (e.g., Ethereum) or not. Other blockchain frameworks used include Hyperledger Sawtooth, IOTA, NEO, Corda, and Multichain. There are also solutions that incorporate other blockchain-based technologies, such as BigchainDB and Polkadot.

Regarding the types of blockchain (RQ6) utilized in the identified solutions, most of them (36%) use private permissioned blockchains, as shown in Figure 10. Also, a

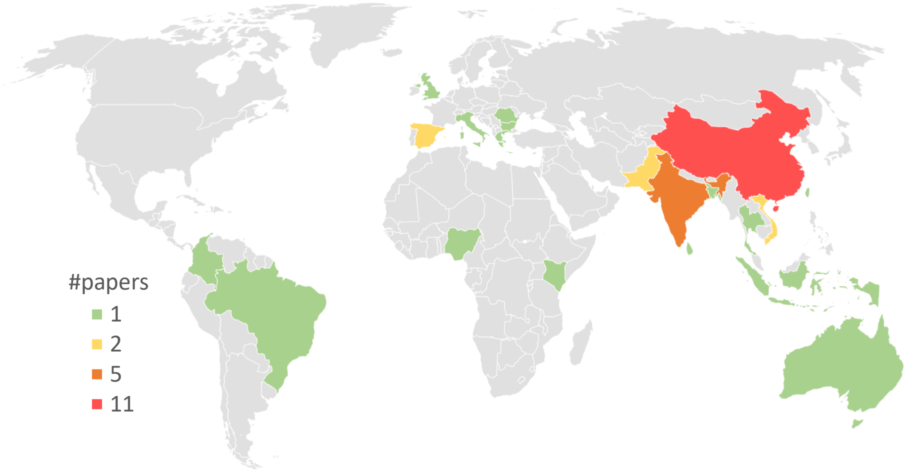


Figure 8. Countries for which the proposed solutions included in our scoping review were created or implemented.

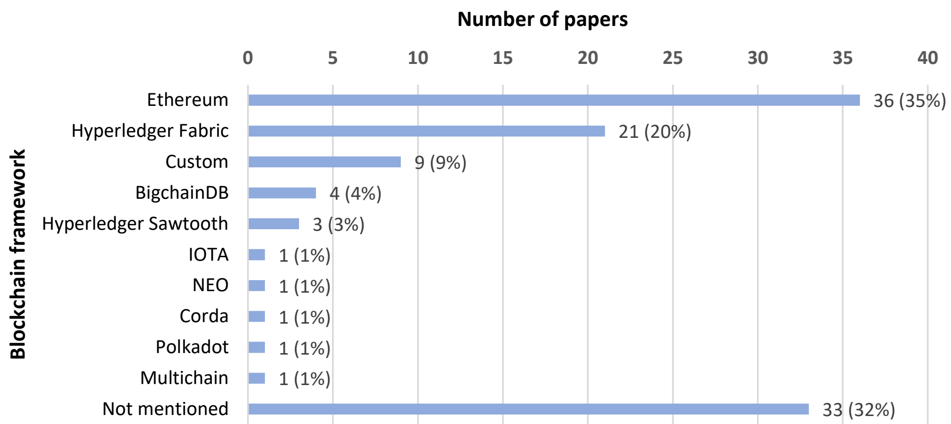


Figure 9. Blockchain technology frameworks considered in the papers included in our scoping review.

significant percentage of papers (28%) use public permissionless blockchains, while 5% of solutions use public permissioned blockchains. Most blockchain frameworks have a specific blockchain type, however, even if Ethereum is public permissionless by default, it is also used as a private permissioned or public permissioned. As we can see, no approach uses private permissioned blockchains, which are rarely used anyway. Finally, five research papers (5%) combine two different types; three papers (3%) combine public permissioned and private permissioned blockchain networks, and two papers (2%) use jointly public permissionless and private permissioned. Finally, in 28 research papers (27%), the type of blockchain is not mentioned.

Analysis of each source identified the data stored in the blockchain in agricultural applications (RQ7). This data varies depending on the solution proposed by each paper, as shown in Figure 11. The most common type of stored data, as reported on 43 papers (41%) (Figure 11a), is data from IoT devices, such as temperature, humidity, etc. It should be noted that many sources do not constantly upload data to the blockchain but only do so when there are anomalies/invasions, something that occurs in 6 papers. In contrast, in another 6 solutions, the data is stored in the blockchain periodically during the day. The aggregate data is usually stored in external databases. It is also common in the identified applications to ask users to provide information about products (29%), farmers (4%), farmland records (3%), seeds (3%), animals (2%), machinery (2%) and ERP data (2%). Additionally, it is common practice to store data outside the blockchain, and its integrity is ensured by storing

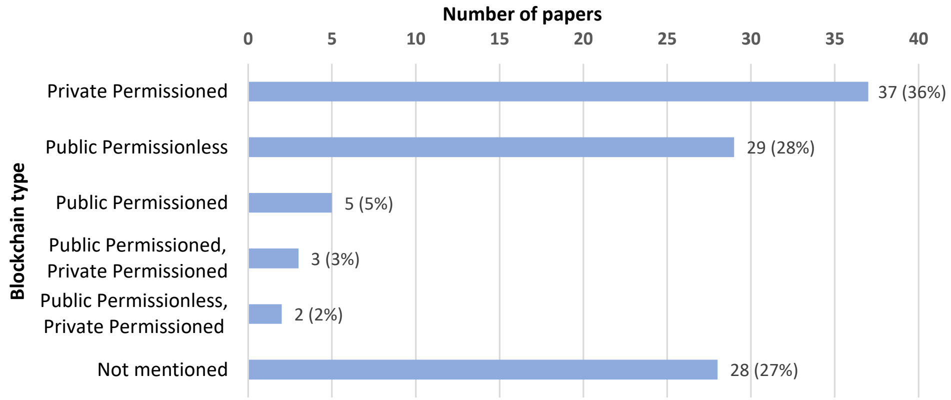
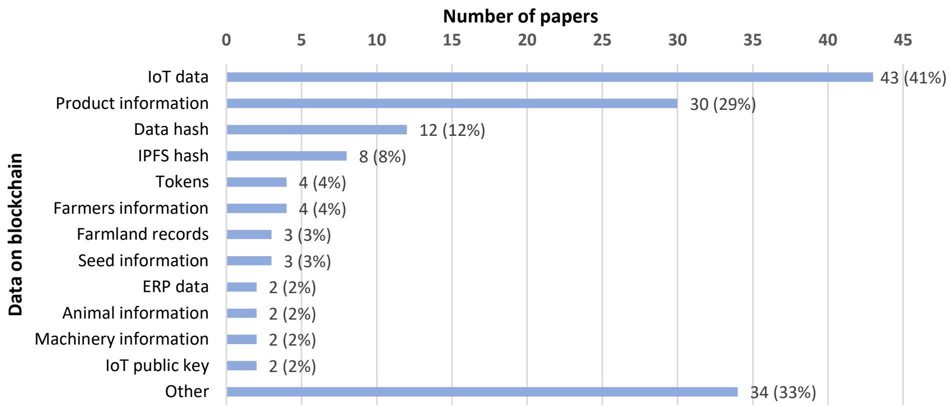


Figure 10. Types of blockchain presented in the papers included in our scoping review.

the hashes of this data in the blockchain. More specifically, we identified 8 papers (8%) that store IPFS files hashes and 12 papers (12%) that store the hashes of data stored in external databases. It is essential to mention that in recent works, the storage of tokens (4%) in blockchain has begun, while there are proposals for the storage of public keys of IoT devices (2%). In addition to all the above data stored in the blockchain, 34 other different data types have been reported in a single solution. Figure 11b shows a word cloud of all the different data types considered in the agricultural blockchain applications included in the scoping review for a visual overview.



(a) Popular data types stored in blockchain.

(b) A word cloud of the total data stored in blockchain.

Figure 11. Types of data stored in the blockchain in the papers included in our scoping review.

The data stored off-chain (RQ8) in the identified solutions is shown in Figure 12. From the 104 research solutions proposed, 37 of them (36%) mention at least one external storage.

Most of the data stored off-chain is IoT data (13%) and product information (12%). Media files (6%), hashes (3%), RFID data (2%), and private data (2%) are also stored off-chain. Less common to be stored externally in research papers are reputation scores (2%), transaction log (1%), GIS data (1%), and credentials (1%). In addition to the data stored externally, we present the storage technology used. No specific technology is mentioned in most of the external data storage solutions (13%). The most common technology used in conjunction with blockchain is IPFS (13%). Also, other distributed storage systems are BigchainDB (2%), QLDB (1%), OurSQL (1%) and a not specific distributed database (1%). Finally, there are solutions that use SQL (4%) and NoSQL (3%, including MongoDB) databases, as well as cloud storage (2%) and BigQuery (1%).

Figure 12. Types of data stored off-chain and the corresponding storage technology used. The groups shown in the external ring are overlapping, that is, some items might belong to more than one group.

Each agriculture application uses blockchain technology for different reasons (RQ9) in order to offer specific advantages in the field of data security, as shown in Figure 13. For example, most papers in agriculture use blockchain for product logging (72%). Also, it is commonly used to achieve transparency (61%), integrity (50%), and traceability (18%). Other uses include ensuring access control to devices or users (6%), scheduling (5%), storage assets (4%), data availability (3%), and finally for incentives (1%).

An overview of the data charting keywords that were identified by our detailed analysis according to the research questions (RQ1 – RQ9) explored in this scoping review is presented as a mind map in Figure 14.

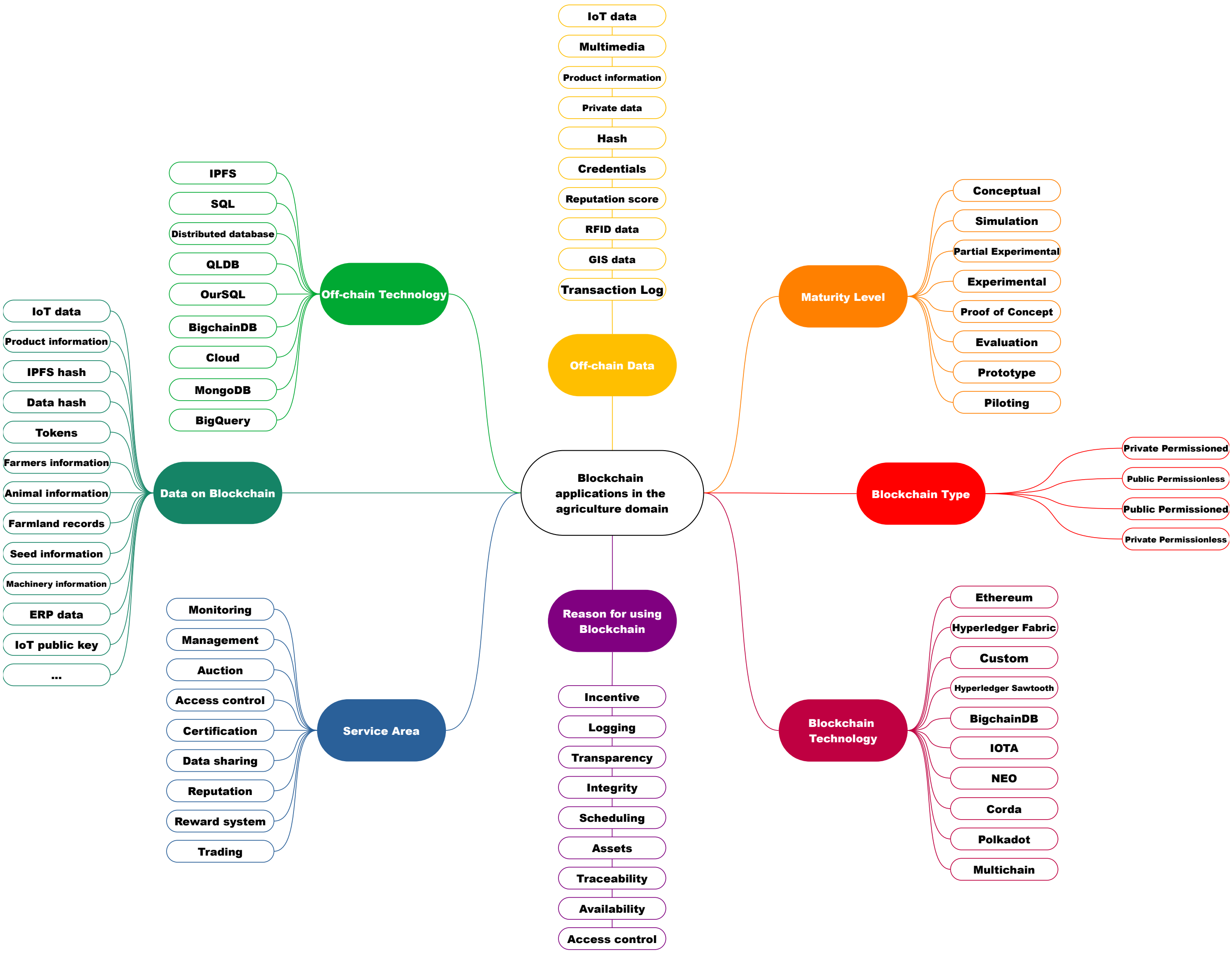


Figure 14. The classification scheme that emerged from the analysis of papers included in this scoping review presented as a mind map.

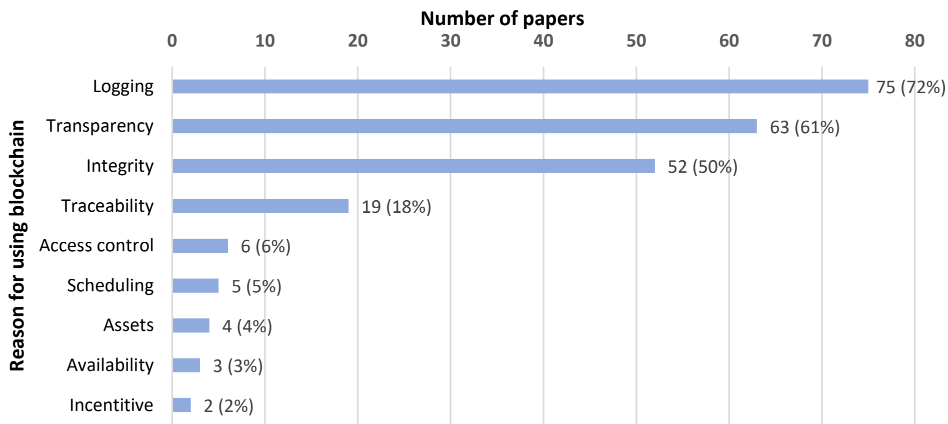


Figure 13. Reasons for using blockchain exploited in the papers included in our scoping review.

4. Discussion

4.1. Summary of Evidence

The primary outcome of this scoping review shows that blockchain technology has so far been proposed to address many issues in several different agricultural applications, as summarized in the following paragraphs.

One of our primary findings was the variations of the specific blockchain framework used (RQ5). The result reflects the situation that prevails in the overall ecosystem of the blockchain. Most solutions use Ethereum and Hypeledger Fabric. Beyond that, a large percentage do not mention the blockchain technology they use. The papers that do not mention technology are mainly conceptual (67%, 22 out of 33papers). Apart from the above in the use of blockchain in the agricultural sector, other technologies have been used less frequently, such as Hypeledger Sawtooth (3%), IOTA (1%), NEO (1%), Corda (1%) and Multichain (1%). Two assistive blockchain-based technologies, BigchainDB (4%) and Polkadot (1%), also appear. Finally, seven research papers in this field combine more than one technology. All these papers use Ethereum combined with another technology [53–58], except one [59]. In one of them [58], Polkadot is used for two-chain communication, which allows cross-blockchain transfers.

Blockchain technologies show the ability to handle various security issues. An important aspect in this direction was the identification of data stored on-chain and off-chain (RQ7 and RQ8). Based on the results of this scoping review, blockchain technology has been proposed more frequently for storing data by sensors and IoT devices in order to monitor specific aspects of the production process. This appears in 43 research papers (41%). This data is mainly used to monitor the process and secondarily used to manage information or the product. In addition to the above, there are four solutions that store access control and authentication policies, for IoT devices, on-chain [60–62], but also off-chain [63]. Some research papers suggest periodical storage of data in the blockchain [55,64–68], so as not to unnecessarily burden the additional cost of storing and using the blockchain. In some cases, an external database is usually used to store the aggregate data [65,66,68]. In the corresponding category of solutions are also approaches that store only anomalies presented in the data from the IoT devices [65,66,69–71]. This is usually to ensure the integrity of the information and not to distort it. Almost all of these solutions that store only critical data in the blockchain have external storage. Both in the case of periodic storage and in the case of abnormal storage, all solutions use Ethereum except one that uses Hyperledger Fabric. This makes sense because, in Ethereum, storage costs are taken into account when creating the architecture.

Another common architectural scheme in creating decentralized applications is to store hashes in the blockchain and actual data in external storage. Most architectures use IPFS to store agriculture data and the blockchain stores either the IPFS hash [72–79] or the data hash [58,59,80]. There is a work [58] that stores data from sensors in IPFS, then the hash of this data is stored in a private permissioned blockchain, while the block hash of this blockchain and the height of the block are stored in Ethereum. In the latter, an incentive mechanism is activated, through a smart contract, to reward the user who did the mining in the private permissioned blockchain. In this way, the authors achieve the security that a private permissioned blockchain would not have.

As reflected in our research, a new trend in the blockchain is the digital representation of real-life assets through a digital twin. A digital twin is a virtual representation of a physical object or system, usually in multiple stages of its life cycle [81]. As Pylianidis *et al.* [82] points out, the use of digital twins could bring significant benefits to the agricultural process. The blockchain has also been proposed to represent digital twins using tokens. The research that has been done represents products as tokens (following ERC20 token standard) that are indirectly related to the agricultural sector, such as water and energy that farmers need to share [54,83]. Their use as currency for transactions between producers and buyers has also been suggested [84]. They can also be used as a reward system for the virtuous use of water [85], where the smart contract is a digital twin of IoT device that monitors water consumption. Due to the lack of infrastructure, the researchers created a module for IoT devices to communicate directly with the smart contract [85,86]. According to our findings, no research has been done on the digital representation of the product, which would help in the certification and traceability of the product from the farm to the fork [87].

In addition to all the above data we have an additional 42 different types of data stored in the blockchain. These may include public keys from IoT data authentication devices, farmer information, farmland records, job description and contract to define the work of some farmers, machine information that can be rented to farmers, RFID data or GIS sensors, blockchain access rules, drone data, pre-orders that may be available, product rating as well as information on seeds, animals, etc. These different types of data show the multiple solutions that blockchain can potentially offer in the agricultural sector.

Another research question that we explored is the maturity level of the solutions (RQ2). One of the main findings was that blockchain applications in the agricultural sector are at a relatively early stage of maturity. More than half of the works (55%) describe the architecture, have done some simulations or have been partially experimental (not in the blockchain). 18% of papers have done experiments to test functionalities of the blockchain, such as its connection to IoT devices and cost issues, while 13% have made a proof of concept of the proposed solution. According to our results, only 7% is at the level of evaluation, 3% at the level of prototyping, and 4% at the level of piloting the solution.

The evaluation of the proposed solutions is achieved using datasets from companies and IoT devices [80,88,89], data created artificially [57,90], and real-world data from the agricultural sector [59,70]. There are also applications in our findings where evaluation is limited to laboratory tests or simulations. Based on our results, we only found three prototype applications [91–93]. All these prototype applications were published from 2020 onwards, showing us that maturity is now growing and real applications are being created. In addition, we identified four solutions in a pilot phase that have been installed, tested, and used in real conditions. The first application [94] is a pilot, mainly in Nigeria, with the aim of renting tractors for agricultural work. In the works proposed by Wang *et al.* [79] and Yang *et al.* [95], the main focus was on traceability of products and have been applied in factories in China. These three applications have been created using Hyperledger Fabric. Finally, another research work [96] uses the IOTA Tangle network to record the data from IoT devices and is in a pilot application in 3 farms in Greece. Interestingly, no application that uses Ethereum as blockchain technology is yet at this maturity level.

As the technology matures and more industrial applications emerge, real-world pilot demonstrations, such as the above, will help shape the field of more mature applications and reveal the most appropriate blockchain applications in the agricultural sector.

The use of blockchain does not focus primarily on a specific product (RQ3), as we found in our research. Instead, there are general terms such as crops, organic food, and water that are mentioned in most studies, but beyond that, there is a dispersion of 31 different products. It is interesting to notice that we have more references to farming products than to animal products. Although the difference is about three times smaller, 39% [e.g., 78,97,98] vs. 14% [e.g., 73,92], a significant percentage (38%) of the solutions do not indicate the industry to be used. A small percentage (9%) refers to goods needed in the agricultural sector, such as water, energy, and proper waste management. This shows us that researchers can focus on specific products that would be in line with blockchain logic but also that there is a need for agnostic solutions in the supply chain.

In this scoping review, we also research the reason for using blockchain in the agriculture sector (RQ9). As a result, most solutions use blockchain for its inherent characteristics, such as data transparency and integrity. This happens at 61% and 50% respectively. Also, few papers (3%) [57,72,99] use another intrinsic feature of blockchain technology, its data availability. It should be mentioned that many solutions involve the use of blockchain over conventional databases due to the availability provided but do not clearly define it, so it has not been included in our respective count. In addition to the above reasons for using blockchain, a typical process is storing product information and tracking information. This data logging is used in most research papers (72%) [e.g., 95,100,101]. It should be noticed that although blockchain is used for logging and storing data, such as IoT data, it should not be misused. Blockchain in general and especially public permissionless blockchains should not be used to store the overall data of an application. Such storage is costly and increases the size of the blockchain, making it non-functional. Insted, blockchain technology should be used as designed to store critical data to which the blockchain gives an immutable feature. Another common reason for using blockchain is traceability, which is found in 18% of solutions [e.g., 57,102]. As before, we need to be aware that some solutions misinterpret that traceability is an inherent feature of blockchain, which is not entirely accurate. Although the ledger itself provides traceability, this possibility cannot be easily and efficiently achieved without a specific architecture and without third-party frameworks [34].

Blockchain has also been used to schedule various processes in the agricultural sector. Scheduling may involve hiring machinery from farmers for specific tasks [94,103] or hiring seasonal workers for agricultural jobs [104]. It may also involve priority scheduling for defined tasks with robots coalitions [99] or fixing IoT devices using autonomous drones [67]. Based on our findings, blockchain technology has also been used to provide access control solutions [60,61,93,105–108]. These solutions store data in the blockchain for access control, such as public keys and access policy. Most devices for which access control is used are IoT devices. Finally, the blockchain has been utilized as an incentive mechanism for the effective management of waste by farmers [109].

Following the research question about the reasons for using blockchain, we examine which service is provided by the respective applications (RQ1). Based on our findings, more than half of the applications have been created to provide product monitoring or management. This is observed in 55% and 75% of the papers, respectively. A unique feature is that most applications (61%), that have been created for products monitoring, store data from IoT devices [e.g., 66,105]. In the case of management, this may relate to the process by which the product went through the various stages of production as well as its resale [e.g., 57,110]. This model of all transaction availability promotes the circular economy model. Most of the time, management and monitoring are combined in the proposed solutions. Management can also refer to the coordination of processes, such as the rental of equipment [94], the use of robots [99], and the proper distribution of a good such as water, energy, or waste [e.g., 83,86,109].

Although not so many applications have been created extensively, one industry that developed mainly after 2019 is product certification (8%). In most cases, the provided solutions certify the authenticity of the product's origin [102,111] and the conditions under which it was developed [69,98]. Therefore, the data stored in the blockchain is related to both the product and the process other than the IoT data. We notice that they refer more often to organic products and are mainly interested in the transparency and integrity provided by the blockchain. Furthermore, a research paper uses GIS to prove the location [111].

A different emerging field of blockchain applications in agriculture is auctions (3%) and product trading (4%). In the first category, we identified three research papers [89, 97,112] that proposed a system of offers for the sale of agricultural products. All these proposed solutions belong to the farming sector. Respectively, there are applications that deal with the trading of either agricultural products [113] or energy and water for crops [54,83]. In addition, there is a proposed solution that exchanges products based on the farmer's rating [114].

Other services provided by agricultural blockchain applications are reputation (4%) and reward systems (3%). The rationale for a reputation system is clear, and such systems aim to capture product and producer ratings. The reason for using blockchain in such applications is the integrity that it provides, something that our research thoroughly verifies [77,78,114,115]. Additionally, blockchain is highly associated with reward system applications. More precisely, we observed that all incentive solutions related to data management, are also indirectly related to blockchain, such as water [85,86] and waste [109]. The validation of the incentive mechanism is performed by the IoT data stored in the blockchain. Finally, one last type of provided service is data sharing and blockchain is used for authentication [106] or as an incentive mechanism as mentioned above [56].

4.2. Limitations

The limitations of this scoping review are related to the publications' maturity and the bibliographic databases included for retrieving publications. Our search looked at some (not all) of the most popular scientific literature indexing systems. Because our research was focused on the scientific literature, we did not take into account the gray literature as well as the real-life implementations, something that can be deduced from the holistic examination of the problem. Our research scope returned heterogeneous data that was not easy to classify for conducting the study, even in our case. Finally, as a limitation, it should be noted that because this field is still in its infancy and most works repeat the same structure in their architecture, while, in some cases, blockchain is used as a panacea.

An additional difficulty was to determine the correct level of maturity in the identified solutions. It was often shady at what stage the provided solutions were, while in other works the terminology we used for the maturity level has different meanings for the authors of the papers. This was primarily solved by precisely defining each maturity level as described in the methodology. Respectively, we had similar limitations in the findings of other research questions in which in several works they were quite general and did not give us the specific data.

5. Conclusions

In this article, our goal was to conduct a scoping review with applications of blockchain technology in the agricultural sector and to identify its advantages. For this purpose, we used the PRISMA-ScR methodology. With the help of scientific bibliographic databases, we found the corresponding sources. Systematically, we analyzed 104 research publications, the largest number of papers in such a study. The research activity in the field started only in 2017 and is constantly increasing, as shown by the demographic data presented in the research.

Although the field is still in its infancy and most of the solutions are conceptual, the research maturity of the papers has shown a development that can be seen in the studies that have started to be applied to the daily life of agricultural activities. Nevertheless, blockchain applications in the agricultural sector are still an emerging field with promising ideas, which is supported by the growing annual distribution of relevant publications.

As the technology matures, other diverse and exciting applications emerge, including emerging technologies, such as IoT devices, robotics, drones, and many others. Therefore, researchers are trying to find exemplary blockchain applications in the agricultural sector. Through this, many exciting solutions have emerged related to traceability, circular economy, incentive systems, etc. However, given the above, although there are ideas, it is clear that integrating new technologies in the traditional agricultural sector is a considerable challenge that should be done step by step and only with the effective involvement of directly affected actors throughout the supply chain.

As we have found in our scoping review, blockchain technology shows that it is very promising in agricultural products; some challenges and obstacles need to be addressed. These are related to the same scalability of blockchain and data storage. Many of the works we have seen do not consider and use blockchain as storage. However, some solutions have addressed this issue and suggest using external databases for data storage and blockchain for data integrity or different purposes. We also believe that the digital representation of the product is an essential step, something for which the research is still in its infancy. Finally, an important issue is the privacy (or confidentiality) of farmers' data and products in the blockchain, which can be studied in future research. Of course, for the right architecture of all the above and the proper development of decentralized applications, developers need to better understand the blockchain and the requirements set by those directly involved.

In the context of our review, we concluded that due to the growing trend of research in this area, such an extensive search in the future would not be possible. However, in future iterations of a similar field overview, search queries should be more specific and focus on specific areas or technological issues, as the retrieved papers will not be manageable. Furthermore, our search returned heterogeneous data that was not easy to classify for conducting the research, even in our case.

In summary, this study can be a starting point for future research into more specific aspects of blockchain applications in the agricultural sector and serve as a reference and guide for similar studies in the future. The blockchain is an up-and-coming technology in various sectors, such as the digitization of the food supply chain, the creation of "smart" farms, and the certification of products, aiming at consumer confidence. However, obstacles and challenges still need to be addressed in order for these applications to spread in everyday life.

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Conflicts of Interest: The authors declare no conflict of interest.

Table 1: Research papers included in the scoping review, their characteristics, the agriculture products on which they focus, and the country of application.

#	Author	Year	Source Type	Service Area	Maturity Level	Agriculture Product	Country
1	Abraham and Santosh Kumar [116]	2020	Conference	Management	Conceptual		India
2	Ahmed *et al.* [117]	2020	Conference	Management (fertilize)	Conceptual		Bangladesh
3	Alonso *et al.* [101]	2020	Journal	Monitoring, Management (IoT platform)	Partial Experimental (not in the blockchain)	Milk	Spain
4	Arena *et al.* [102]	2019	Conference	Certification (olive)	Experimental	Extra virgin oil	
5	Arshad *et al.* [60]	2020	Conference	Monitoring (with Access control)	Partial Experimental (not in the blockchain)		Pakistan
6	Awan *et al.* [118]	2020	Journal	Monitoring (IoT with energy efficiency)	Simulation (Matlab)		
7	Awan *et al.* [72]	2020	Conference	Monitoring, Management (crop)	Simulation (Matlab)	Crops, Grains	Pakistan
8	Bakare *et al.* [91]	2021	Conference	Management (subsidies)	Prototype		India
9	Balakrishna Reddy and Ratna Kumar [113]	2020	Conference	Certification (quality), automate trading	Conceptual	Organic food	India
10	Basnayake and Rajapakse [98]	2019	Conference	Management, certification (organic food)	Proof of Concept	Organic food	Sri Lanka
11	Bechtsis *et al.* [119]	2019	Conference	Monitoring, Management	Proof of Concept		
12	Benedict *et al.* [70]	2020	Conference	Monitoring (rubber manufucture)	Evaluation	Rubber	India
13	Bordel *et al.* [55]	2019	Conference	Monitoring, Management (irrigation system)	Partial Experimental (not in the blockchain)	Water	
14	Bore *et al.* [94]	2020	Conference	Management (tractor leasing)	Piloting		Nigeria
15	Branco *et al.* [120]	2019	Conference	Monitoring, Management (mushroom)	Conceptual	Mushrooms	
16	Cao *et al.* [92]	2021	Journal	Monitoring, Certification (beef)	Prototype	Beef	Australia, China
17	Caro *et al.* [57]	2018	Conference	Management (crop)	Evaluation		
18	Casado-Vara *et al.* [121]	2018	Conference	Management	Conceptual		
19	Chen *et al.* [122]	2021	Journal	Management	Simulation (Python)	Corn (use case)	
20	Chinnaiyan and Balachandar [53]	2020	Conference	Monitoring, Management (IoT, drones)	Conceptual		
21	Chun-Ting *et al.* [123]	2020	Conference	Monitoring	Conceptual		
22	Cong An *et al.* [124]	2019	Conference	Monitoring, Management	Proof of Concept		
23	Dawaliby *et al.* [67]	2020	Conference	Monitoring (farm), Management (drone operations)	Proof of Concept		
24	Dey *et al.* [125]	2021	Journal	Certification (product with QR code)	Simulation (Python)	Milk, Pumpkin	UK
25	Dong *et al.* [64]	2019	Conference	Monitoring, Management	Conceptual	Camellia oil	
26	Du *et al.* [73]	2020	Conference	Monitoring, Management	Partial Experimental (concensus protocol)		
27	Enescu *et al.* [54]	2020	Journal	Management, Trading (energy)	Proof of Concept	Photovoltaic, Water	Romania

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#	Author	Year	Source Type	Service Area	Maturity Level	Agriculture Product	Country
28	Enescu and Manuel Ionescu [84]	2020	Conference	Monitoring, Management	Conceptual		
29	Friha *et al.* [61]	2020	Conference	Access control, Management (SDN IoT devices)	Experimental		
30	Hang *et al.* [105]	2020	Journal	Monitoring	Proof of Concept	Fish	
31	Hao *et al.* [74]	2018	Journal	Monitor, Management, Certification	Experimental		
32	Harshavardhan Reddy *et al.* [126]	2019	Journal	Management (economic efficiency)	Conceptual		
33	Hong *et al.* [127]	2019	Conference	Monitoring, Management	Conceptual	Chicken (use case)	
34	Hu *et al.* [59]	2021	Journal	Monitoring, Management (organic food)	Evaluation	Organic food, Citrus (use case)	China
35	Iqbal and Butt [128]	2020	Journal	Monitoring (animal invesion), Management (crop)	Partial Experimental (not in the blockchain)	Crops	
36	Iswari *et al.* [129]	2019	Conference	Monitoring, Management	Conceptual	Coccoa	Indonesia
37	Jaiswal *et al.* [97]	2019	Conference	Management, Auction	Experimental	Grain	
38	Jaiyen *et al.* [130]	2020	Conference	Monitoring, Management	Proof of Concept		
39	Jiang *et al.* [131]	2020	Conference	Management	Conceptual	Chicken (use case)	
40	Kawakura and Shibasaki [132]	2019	Journal	Monitoring (hoe's movement)	Experimental	Hoe	
41	Khan *et al.* [88]	2020	Journal	Monitoring, Management (with deep learning)	Evaluation		
42	Krasteva *et al.* [133]	2020	Conference	Management (genes)	Conceptual	Genes	Bulgaria
43	Kumar *et al.* [80]	2021	Journal	Privacy preserving management (UAV)	Evaluation		
44	Lamtzidis *et al.* [96]	2019	Journal	Monitoring, Management	Piloting	Vineyards (use case)	Greece
45	Leme *et al.* [134]	2020	Conference	Monitoring	Conceptual	Cows	Brazil
46	Leng *et al.* [110]	2018	Journal	Management (supply chain)	Simulation (Matlab)		China
47	Liao and Xu [135]	2019	Conference	Monitoring, Management (quality safety)	Conceptual	Tea	
48	Lin *et al.* [136]	2018	Conference	Monitoring, Management	Conceptual		
49	Lin *et al.* [137]	2017	Journal	Monitoring (water)	Conceptual	Water	Taiwan
50	Liu *et al.* [71]	2018	Journal	Monitoring, Management	Experimental		
51	Lu *et al.* [106]	2020	Conference	Authenticated data sharing system	Conceptual	Crops	
52	Madhu *et al.* [138]	2020	Conference	Monitoring, Management (crop)	Proof of Concept	Crops	
53	Mao *et al.* [89]	2018	Journal	Management, Auction	Evaluation	Wheat, Corn, Soybean	China
54	Marinello *et al.* [139]	2017	Conference	Management	Conceptual	Meat	Italy
55	Meidayanti *et al.* [140]	2019	Conference	Monitoring, Management	Conceptual	Beef	
56	Miloudi *et al.* [69]	2020	Conference	Management, Certification (crop)	Conceptual	Crops	
57	Murali and Chatrapathy [114]	2019	Journal	Reputation system, Trading	Partial Experimental (not in the blockchain)		

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Table 1 – *continued from previous page*

#	Author	Year	Source Type	Service Area	Maturity Level	Agriculture Product	Country
58	Nadeem Akram *et al.* [141]	2020	Conference	Management (with QR)	Conceptual	Apple (use case)	India
59	Nguyen *et al.* [142]	2020	Conference	Management	Conceptual	Crops	Vietnam
60	Nguyen *et al.* [100]	2019	Conference	Management (insurance for disasters)	Experimental	Crops	Vietnam
61	Orjuela *et al.* [90]	2021	Journal	Monitoring, Management	Evaluation		Colombia
62	Osmanoglu *et al.* [115]	2020	Journal	Management, Reputation system	Conceptual	Crops	
63	Öztürk *et al.* [143]	2021	Conference	Monitoring (livestock welfare with machine learning)	Conceptual	Cows	Spain
64	Paul *et al.* [144]	2019	Conference	Management (loaning sytem)	Proof of Concept	Crops	
65	Pincheira *et al.* [56]	2020	Conference	Data sharing (incentive mechanism)	Conceptual		
66	Pincheira *et al.* [86]	2020	Conference	Monitoring, Management (water), Reward system	Partial Experimental (not in the blockchain)	Water	
67	Pincheira *et al.* [85]	2021	Journal	Monitoring, Management (water), Reward system	Experimental	Water	
68	Pinna and Ibba [104]	2019	Conference	Management (temporary employing contract)	Conceptual		
69	Pooja *et al.* [112]	2020	Conference	Management, Auction	Conceptual	Seeds, Crops	
70	Pranto *et al.* [65]	2021	Journal	Monitoring, Management	Experimental		
71	Prashar *et al.* [75]	2020	Journal	Monitoring, Management	Experimental		India
72	Raboaca *et al.* [83]	2020	Journal	Management, trading (energy)	Proof of Concept	Photovoltaic, Water	
73	Rambim and Awuor [145]	2020	Conference	Management (milk delivery system)	Conceptual	Milk	Kenya
74	Ren *et al.* [58]	2021	Journal	Secure Management (double chain)	Experimental		
75	Revathy and Sathya Priya [146]	2020	Conference	Management	Conceptual	Crops	
76	Saji *et al.* [147]	2020	Conference	Management	Conceptual		
77	Salah *et al.* [76]	2019	Journal	Monitoring, Management	Conceptual	Soybean	
78	Saurabh and Dey [148]	2021	Journal	Monitoring, Management	Conceptual	Wine (use case)	
79	Shahid *et al.* [77]	2020	Journal	Monitoring, Management, Reputation system	Experimental	Crops	
80	Shahid *et al.* [78]	2020	Conference	Monitoring, Management, Reputation system	Experimental	Crops	
81	Shih *et al.* [111]	2019	Journal	Certification	Experimental	Organic Food	
82	Shyamala Devi *et al.* [149]	2019	Conference	Monitoring	Proof of concept		
83	Smirnov *et al.* [99]	2020	Conference	Management (robot coalition for precision farming)	Conceptual	Crops	
84	Son *et al.* [68]	2021	Journal	Monitoring, Management	Proof of concept		
85	Surasak *et al.* [150]	2019	Journal	Monitoring, Management	Proof of concept	Beef	Thailand
86	Tan and Zhang [151]	2021	Journal	Monitoring (for authenticate loans)	Partial Experimental (not in the blockchain)		
87	Umamaheswari *et al.* [152]	2019	Conference	Management	Proof of Concept	Crops	
88	Vangala *et al.* [63]	2021	Journal	Access control (safe IoT), Monitoring	Experimental		

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Table 1 – *continued from previous page*

#	Author	Year	Source Type	Service Area	Maturity Level	Agriculture Product	Country
89	Wang *et al.* [153]	2020	Conference	Management (anti-counterfeiting)	Conceptual		
90	Wang *et al.* [79]	2021	Journal	Monitoring, Management	Piloting	Crops	China
91	Wang and Liu [154]	2019	Conference	Monitoring	Conceptual		
92	Wu and Tsai [62]	2019	Journal	Access control (secure system)	Partial Experimental (not in the blockchain)		
93	Xie *et al.* [66]	2017	Conference	Monitoring	Experimental		
94	Xie and Xiao [155]	2021	Conference	Monitoring (quality of product)	Conceptual		China
95	Xie *et al.* [156]	2019	Conference	Monitoring, Management	Experimental		China
96	Yang and Sun [157]	2020	Conference	Management	Conceptual		China
97	Yang *et al.* [103]	2020	Journal	Management (leasing scheduling system)	Simulation		
98	Yang *et al.* [107]	2020	Conference	Monitoring (livestock)	Conceptual		
99	Yang *et al.* [95]	2021	Journal	Monitoring, Management	Piloting	Fruit, Vegetables	China
100	Yi *et al.* [158]	2020	Conference	Management	Experimental		
101	Yu *et al.* [159]	2020	Conference	Monitoring, Management (transaction, quality)	Experimental		
102	Zhang [109]	2019	Conference	Management (wastes), Reward system	Conceptual	Wastes	China
103	Zhang *et al.* [93]	2020	Journal	Monitoring, Management	Prototype	Grain	China
104	Zhaoliang *et al.* [108]	2021	Journal	Monitoring (privacy preserving)	Simulation (not in the blockchain)		

Table 2: Descriptive data on the particular blockchain application presented in each of the papers included in the scoping review.

#	Author	Blockchain Technology	Blockchain Type	Data on Blockchain	Off-chain Data	Reason for using Blockchain
1	Abraham and Santosh Kumar [116]	Hyperledger Fabric	Private Permissioned	Farmer information		Transparency, Logging
2	Ahmed *et al.* [117]	Hyperledger Fabric	Private Permissioned	Fertilizer information		Integrity, Logging
3	Alonso *et al.* [101]			IoT data hash	IoT data (BigQuery)	Integrity, Traceability, Logging
4	Arena *et al.* [102]	Hyperledger Fabric	Private Permissioned	IoT data		Integrity, Logging, Traceability
5	Arshad *et al.* [60]	Hyperledger Fabric	Private Permissioned	IoT data, Policy headers, Access records		Access control, Integrity, Logging
6	Awan *et al.* [118]			IoT data		Integrity, Logging
7	Awan *et al.* [72]			IPFS hash	Product growth information, Media files (IPFS)	Integrity, Availability
8	Bakare *et al.* [91]	Custom	Public Permissioned	Farmland records		Transparency, Logging

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Table 2 – *continued from previous page*

#	Author	Blockchain Technology	Blockchain Type	Data on Blockchain	Off-chain Data	Reason for using Blockchain
9	Balakrishna Reddy and Ratna Kumar [113]	Ethereum	Public Permissionless	Product information		Transparency, Logging
10	Basnayake and Rajapakse [98]	Ethereum	Public Permissionless	Production process		Transparency, Logging
11	Bechtsis *et al.* [119]	Hyperledger Fabric	Private Permissioned	Product information		Integrity, Logging
12	Benedict *et al.* [70]	Hyperledger Fabric	Private Permissioned	IoT data (anomalies)		Integrity, Logging
13	Bordel *et al.* [55]	Ethereum, -	Public Permissioned, Private Permissioned	IoT data (periodically), Data hash		Integrity, Logging
14	Bore *et al.* [94]	Hyperledger Fabric	Private Permissioned	IoT data, Farmland records, Machinery information		Integrity, Transparency, Scheduling, Logging
15	Branco *et al.* [120]			Data hash	IoT data	Integrity
16	Cao *et al.* [92]	Ethereum	Public permissionless	Product information		Transparency, Logging, Traceability
17	Caro *et al.* [57]	Ethereum, Hyperledger Sawtooth	Public Permissioned, Private Permissioned	IoT data		Transparency, Availability, Logging, Traceability
18	Casado-Vara *et al.* [121]			Trading information		Transparency, Logging
19	Chen *et al.* [122]			Product Information		Integrity, Logging
20	Chinnaiyan and Balachandar [53]	Ethereum, Multichain	Private Permissioned	IoT data, Drone data		Integrity, Logging
21	Chun-Ting *et al.* [123]	Ethereum	Private Permissioned	IoT data		Integrity
22	Cong An *et al.* [124]	Ethereum	Public Permissionless	Product information		Transparency, Logging, Traceability
23	Dawaliby *et al.* [67]	Ethereum	Private Permissioned	IoT data (periodically), Drone operation		Integrity, Logging, Scheduling
24	Dey *et al.* [125]	Custom		Product information	Farm information, Manufacturing information	Transparency, Logging
25	Dong *et al.* [64]			IoT public key, IoT data (periodically)		Integrity
26	Du *et al.* [73]	Hyperledger Fabric	Private Permissioned	IPFS hash	Product information (IPFS), Private data	Integrity
27	Enescu *et al.* [54]	Ethereum, BigchainDB	Public Permissionless	Tokens (ERC20)	Sources information, Personal information (BigchainDB, SQL)	Transparency, Assets
28	Enescu and Manuel Ionescu [84]	Ethereum	Public Permissionless	Tokens (ERC20)	Product information (distributed database)	Transparency, Assets
29	Friha *et al.* [61]	Hyperledger Sawtooth	Private Permissioned	IoT devices, IoT data, SDN rules		Integrity, Access control, Logging
30	Hang *et al.* [105]	Hypeledger Fabric	Private permissioned	Iot data, Product information, Access policy		Integrity, Logging, Access control

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Table 2 – *continued from previous page*

#	Author	Blockchain Technology	Blockchain Type	Data on Blockchain	Off-chain Data	Reason for using Blockchain
31	Hao *et al.* [74]	Ethereum	Public Permissionless	IPFS hash	IoT data, Media files (IPFS), Blockchain transaction hash	Integrity
32	Harshavardhan Reddy *et al.* [126]			Product information		Transparency, Logging
33	Hong *et al.* [127]	Hyperledger Fabric	Private Permissioned	IoT data, Product information		Transparency, Logging, Traceability
34	Hu *et al.* [59]	Custom, BigchainDB	Private Permissioned	Data hash	IoT data (IPFS), Data hash (BigchainDB)	Integrity
35	Iqbal and Butt [128]			IoT data (animal invesion), Product information		Transparency, Logging
36	Iswari *et al.* [129]			Product information		Transparency, Logging
37	Jaiswal *et al.* [97]	Ethereum	Public Permissionless	Product information		Integrity, Transparency, Logging
38	Jaiyen *et al.* [130]	Hyperledger Fabric	Private Permissioned	IoT data		Transparency, Logging, Traceability
39	Jiang *et al.* [131]			IoT data		Transparency, Logging, Traceability
40	Kawakura and Shibasaki [132]	Corda	Private Permissioned	IoT data (hoe)		Logging
41	Khan *et al.* [88]	Hyperledger Fabric	Private Permissioned	IoT data		Logging, Traceability
42	Krasteva *et al.* [133]		Private Permissioned	Genes information		Integrity, Logging
43	Kumar *et al.* [80]	Ethereum (custom consensus)	Public Permissioned	Data hash	IoT data (IPFS)	Integrity
44	Lamtzidis *et al.* [96]	IOTA	Public Permissionless	IoT data	IoT data (MongoDB)	Integrity, Logging
45	Leme *et al.* [134]		Private Permissioned	Data hash	RFID data	Integrity
46	Leng *et al.* [110]	Custom (2 chains)	Public Permissionless	Transaction information, Product information, Personal data hash		Integrity, Transparency, Logging, Traceability
47	Liao and Xu [135]	Ethereum	Public Permissionless	Data hash	Product information (MySQL)	Integrity
48	Lin *et al.* [136]			IoT data, ERP data		Transparency, Logging, Traceability
49	Lin *et al.* [137]			IoT data	IoT data	Integrity, Logging
50	Liu *et al.* [71]	Ethereum	Public Permissionless	IoT data (anomalies)	IoT data (IPFS), Hash	Integrity, Logging
51	Lu *et al.* [106]			IoT data , IoT public keys		Logging, Access control
52	Madhu *et al.* [138]			IoT data		Integrity, Transparency, Logging
53	Mao *et al.* [89]	Ethereum (custom FTSCON)	Private Permissioned	Product information		Integrity, Logging
54	Marinello *et al.* [139]			Animal information		Integrity, Logging, Traceability

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Table 2 – *continued from previous page*

#	Author	Blockchain Technology	Blockchain Type	Data on Blockchain	Off-chain Data	Reason for using Blockchain
55	Meidayanti *et al.* [140]		Public Permissionless	Animal information		Integrity, Logging, Traceability
56	Miloudi *et al.* [69]	Ethereum	Public Permissionless	IoT data, GIS data (anomalies)	IoT data, GIS data	Transparency, Logging
57	Murali and Chatrapathy [114]			Product ratings		Integrity
58	Nadeem Akram *et al.* [141]		Private Permissioned	Product information		Transparency, Logging
59	Nguyen *et al.* [142]	Ethereum or Private Network	Public Permissionless or Private Permissioned	Product information, Pre-orders	Manufacturers private data	Integrity, Transparency, Logging
60	Nguyen *et al.* [100]	NEO	Public Permissioned	IoT data, Insurance information	Farmers profile	Transparency, Logging
61	Orjuela *et al.* [90]	BigchainDB	Private Permissioned	Product information		Logging
62	Osmanoglu *et al.* [115]		Public Permissioned	Farmer yield commitment, Reputation score		Integrity
63	Öztürk *et al.* [143]			IoT data		Integrity, Logging
64	Paul *et al.* [144]	Ethereum	Public Permissionless	Farmer information, Product information, Seed information		Transparency, Logging
65	Pincheira *et al.* [56]	Ethereum, Hyperledger Fabric	Public Permissioned, Private Permissioned	Product information metadata		Integrity, Logging, Incentive
66	Pincheira *et al.* [86]	Ethereum	Public Permissionless	IoT data		Integrity, Transparency, Logging
67	Pincheira *et al.* [85]	Ethereum	Public Permissionless	IoT data, Tokens (ERC20)		Integrity, Transparency, Logging, Assets
68	Pinna and Ibba [104]			Job description, Contract, Wages		Integrity, Transparency, Scheduling
69	Pooja *et al.* [112]	Ethereum	Public Permissionless	Product information, Seed information		Transparency, Logging, Traceability
70	Pranto *et al.* [65]	Ethereum	Public Permissionless	IoT data (anomalies periodically), Product information	IoT data (NoSQL)	Integrity, Transparency, Logging
71	Prashar *et al.* [75]	Ethereum	Private Permissioned	Product basic information, IPFS hash, Hash of previous product	Product information, Media files (IPFS)	Integrity, Transparency
72	Raboaca *et al.* [83]	Ethereum	Public Permissionless	Tokens (ERC20)	Sources information, Personal information (QLDB)	Transparency, Assets
73	Rambim and Awuor [145]			Farmer information, Product information		Transparency, Logging

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Table 2 – *continued from previous page*

#	Author	Blockchain Technology	Blockchain Type	Data on Blockchain	Off-chain Data	Reason for using Blockchain
74	Ren *et al.* [58]	Ethereum, Custom (ASDS ethereum based), Polkadot	Public Permissionless, Private Permissioned	Data hash (Custom), Block hash (Ethereum)	IoT data (IPFS)	Integrity
75	Revathy and Sathya Priya [146]	Ethereum	Public Permissionless	Transactions information		Transparency, Logging
76	Saji *et al.* [147]	Hyperledger Fabric	Private Permissioned	Product information		Integrity, Logging
77	Salah *et al.* [76]	Ethereum	Public Permissionless	IPFS hash, Seed information, Product information, Parties information	Media files (IPFS)	Integrity, Logging, Traceability
78	Saurabh and Dey [148]			IoT data		Integrity, Logging, Traceability
79	Shahid *et al.* [77]	Ethereum	Public Permissionless	IPFS hash	Reputation score, Product information (IPFS)	Integrity, Transparency
80	Shahid *et al.* [78]	Ethereum	Public Permissionless	IPFS hash	Reputation score, Product information (IPFS)	Integrity, Transparency
81	Shih *et al.* [111]	Ethereum	Public Permissionless	Product information, Organic food inspection agency results		Integrity, Transparency, Logging
82	Shyamala Devi *et al.* [149]	Ethereum	Private Permissioned	IoT data		Integrity, Transparency, Logging
83	Smirnov *et al.* [99]	Hyperledger Fabric	Private Permissioned	Resources, Tasks, IoT data		Availability, Scheduling
84	Son *et al.* [68]	Ethereum	Public Permissionless	IoT data (periodically)	IoT data (MongoDB)	Integrity, Transparency, Logging
85	Surasak *et al.* [150]				IoT data (OurSQL)	Integrity, Transparency, Logging
86	Tan and Zhang [151]					Transparency
87	Umamaheswari *et al.* [152]	Ethereum	Public Permissionless	IoT data		Transparency, Logging
88	Vangala *et al.* [63]	Hyperledger Sawtooth	Private Permissioned	IoT data	Credentials (Cloud)	Integrity, Logging
89	Wang *et al.* [153]	Custom (JD)		Product information		Integrity, Logging, Traceability
90	Wang *et al.* [79]	Hyperledger Fabric	Private Permissioned	IPFS hash	Product information, Media files (IPFS)	Integrity
91	Wang and Liu [154]	Hyperledger Fabric	Private Permissioned	Product basic information	Information, Media files	Transparency
92	Wu and Tsai [62]		Private Permissioned	IoT data		Integrity, Logging
93	Xie *et al.* [66]	Ethereum	Public Permissionless	IoT data (anomalies periodically), Parent transaction hash	IoT data	Integrity, Logging

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Table 2 – *continued from previous page*

#	Author	Blockchain Technology	Blockchain Type	Data on Blockchain	Off-chain Data	Reason for using Blockchain
94	Xie and Xiao [155]		Private Permissioned	Product information		Integrity, Logging, Traceability
95	Xie *et al.* [156]	Hyperledger Fabric	Private Permissioned	IoT data		Integrity, Logging, Traceability
96	Yang and Sun [157]	BigchainDB			Transaction logs (IPFS), Farmer, Consumer, Transaction information (MySQL)	Transparency
97	Yang *et al.* [103]	Custom	Private Permissioned	Machinery information, Farmland records, Scheduling data		Scheduling, Transparency
98	Yang *et al.* [107]		Public Permissioned	RFID Access control	Product information, RFID data	Access control, Transparency
99	Yang *et al.* [95]	Hyperledger Fabric	Private Permissioned	Encrypted product private data, Hash of public data	Product public information (MySQL)	Transparency, Logging
100	Yi *et al.* [158]	Ethereum	Public Permissionless	IoT data		Transparency
101	Yu *et al.* [159]	Hyperledger Fabric	Private Permissioned	Product information, IoT data, ERP data		Transparency, Logging
102	Zhang [109]			IoT data, Farmer information		Transparency, Incentive
103	Zhang *et al.* [93]	Hyperledger Fabric	Private Permissioned	Data hash	Product information, Product information encoded	Integrity, Logging
104	Zhaoliang *et al.* [108]			Hash of user data, Authentication information, Encrypted product information	Product information (Cloud)	Integrity, Access control, Logging

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