STM JOURNALS

Journal of
Advanced Database
Management & Systems

ISSN: 2393-8730
Volume 11, Issue 1, 2024
January—April
DOI (Journal): 10.37591/JoADMS

https://journals.stmjournals.com/joadms

Review JoADMS

The Applications, Impact, and Future of Blockchain Technology in Agriculture

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Abstract

Blockchain is one of the most interesting and controversial research topics today. Blockchain technology was first deployed in the financial sector. Nevertheless, it is currently applied in various domains, including healthcare, smart cities, smart contracts, energy markets, and the government sector. The efficacy of this technology primarily depends on the following attributes: reliability, transparency, and immutability. This article gathers and examines the primary contributions from the literature regarding the utilization of blockchain in the agricultural sector, with a specific emphasis on challenges related to food traceability. With the rapid development of this technology and the large amount of literature published in recent months, it is necessary to catalog the different methods proposed by different researchers. Our objective is to uncover prevailing research trends and potential future challenges. In the agricultural realm, the necessity for a comprehensive traceability system arises due to various issues and practices. For instance, the extensive use of pesticides and fertilizers in fruits and vegetables poses a severe threat to human health. Additionally, over the past years, there has been a substantial increase in consumer interest regarding the quality of agricultural products. Ongoing research indicates that blockchain technology is still in its early stages. Despite numerous proposals in the literature, the practical implementation of these applications is limited. From a scientific research perspective, only a handful of countries are actively investing in this technology, with China and the United States being among the most engaged, while Italy is also deeply involved in this phenomenon. Overall, blockchain technology seems very promising, but many efforts still need to be made to reach the maturity stage.

Keywords: Blockchain, literature review, agricultural supply chain, food traceability, internet of things

INTRODUCTION

Blockchain is one of the most interesting and debated research topics today. Blockchain can be defined as "an immutable ledger for recording transactions, maintained in a distributed network of mutually untrusted nodes". The blockchain is an ordered list of blocks, where each block stores a variable-sized list of transactions [1]. The first blockchain was introduced by Satoshi Nakamoto who proposed the concept of cryptocurrency Bitcoin in 2008. This famous and recognized application of blockchain in the financial sector enabled the exchange of digital currencies in a thrustless network of anonymous nodes, with no intermediary third party (i.e. central bank) [2]. However, blockchain technology is currently being used in many other fields, such as: healthcare [3, 4], smart cities [5], smart contracts [6, 7], energy markets quantity [8], government [9], etc. The success of this technology mainly lies in the

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Received Date: February 15, 2024
Accepted Date: February 19, 2024
Published Date: April 03, 2024

Citation: Jaydeep Ramniklal Ramani. The Applications, Impact, and Future of Blockchain Technology in Agriculture. Journal of Advanced Database Management & Systems. 2024; 11(1): 12–22p.

following characteristics: reliability, transparency, and immutability. In this study, we focus on the application of blockchain in agricultural supply chains to ensure food traceability.

The agricultural supply chain can be defined as the set of actors involved in the cultivation, distribution, processing, and marketing of agricultural and horticultural products, "from field to fork eat" [10]. Food traceability is a topic of great importance today and many frameworks have been documented in recent decades to avoid food scandals like those that have occurred in the past. However, blockchain food traceability link is very new and still unexplored. Food traceability is a regulatory term, even if it has slightly different characteristics depending on the geographical area [11].

In the agricultural context, the need for traceability systems is driven by a multitude of bad habits and problems. Firstly, the widespread use of pesticides and fertilizers in fruits and vegetables leads to residues in the final product, which is very harmful to human health. Hormones and other substances, widely used during the growing stage, have the effect of reducing ripening time and thus increasing yield in the field. In some cases, mineral oil is even used to thin biscuits and rice. All these practices not only reduce the nutritional value of agricultural products but also pose great risks to consumer safety [12].

The main objective of this study is to review the literature on blockchain applications in agricultural supply chains, focusing on food traceability issues. To the best of our knowledge, this is the first review to explore in depth the connection between blockchain and food traceability, in an agricultural context. For completeness, Bermeo-Almeida *et al.* also has another review related to blockchain and agriculture [13], but it is more general than this review on the topics covered, and does not focus on food traceability. Furthermore, due to the very rapid development of blockchain and the large number of contributions published in recent months, there is a need to collect, catalog and classify the various proposed methods, with the purpose of understanding search trends and possible future directions or challenges. We collected studies until September 2019.

RESEARCH METHODOLOGY

Our research method is characterized by the following steps:

1. Data collection and analysis;
2. Data selection; and
3. Literature review and discussion.

The first phase involves the collection of scientific articles using appropriate keywords. These contributions were analyzed to highlight the following quantitative aspects: number of articles and relative citations per year, document type, geographical location of authors, keyword statistics, search trends. This step is partly supported by the free software VOS viewer (version 1.6.13), which allows you to create and visualize directory networks [14].

In the second phase, we focused on a subset of the identified research trends and systematically selected scientific articles of interest, according to the inclusion/category criteria except certain (for example, the language of the article). At the final stage, the selected articles were reviewed. Next, a discussion of issues, research trends, future developments, and/or challenges is provided.

DATA COLLECTION AND ANALYSIS

The dataset for this study was created with Scopus at the end of September 2019. Scopus is one of the leading and most recognized databases in scientific research. First, the term "blockchain" was used as a search key in Scopus "literature search" to get a general and quantitative view of this phenomenon. In Figures 1 and 2, we show published articles and citation counts over years during the period 2013–2019, respectively, excluding the following document types: "Conference reviews," "Notes", "Editorial".

Publications: Number and Type Over the Years

In Figure 3, the number and type of publications, over the years, about the topic blockchain-agriculture is shown.

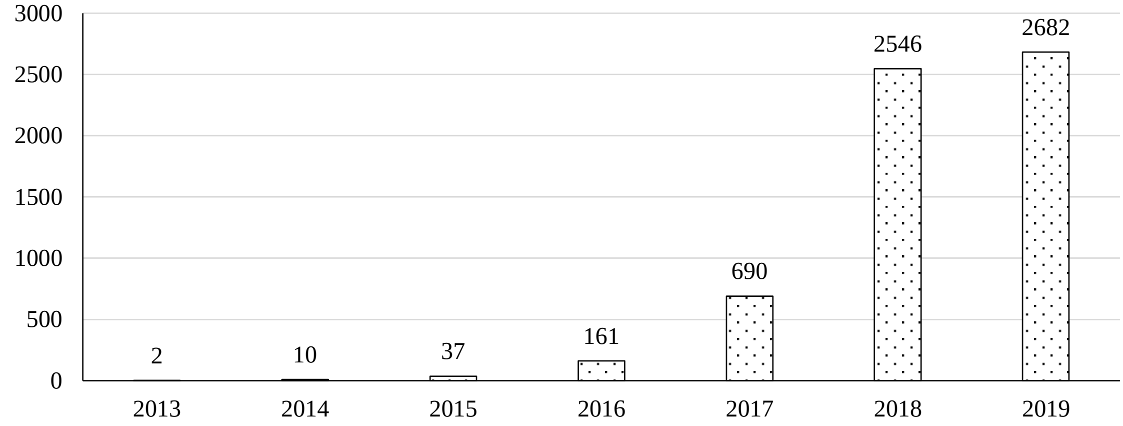

Figure 1. Number of published papers per year about blockchain topic, on the period 2013–2019.

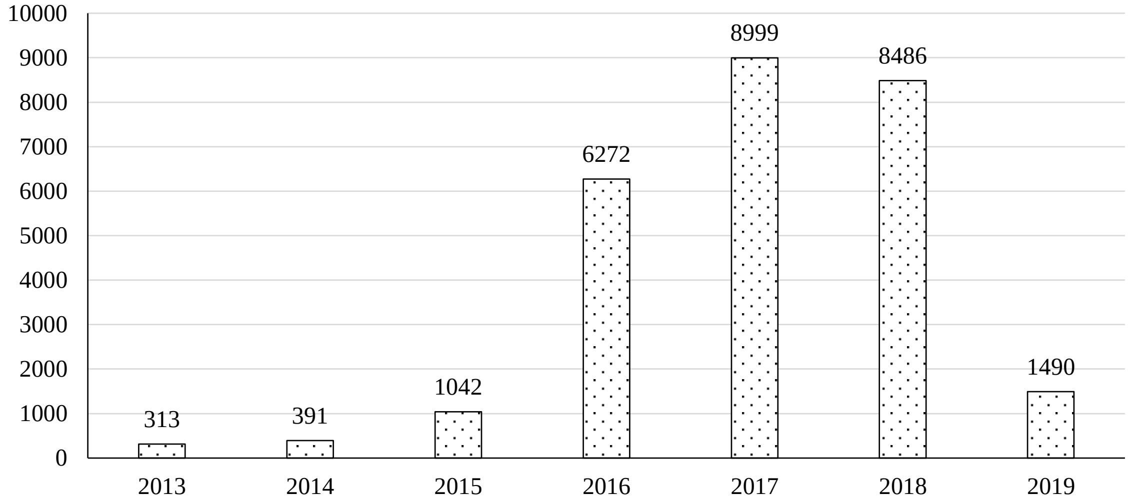

Figure 2. Number of citations per year about blockchain topic, on the period 2013–2019.

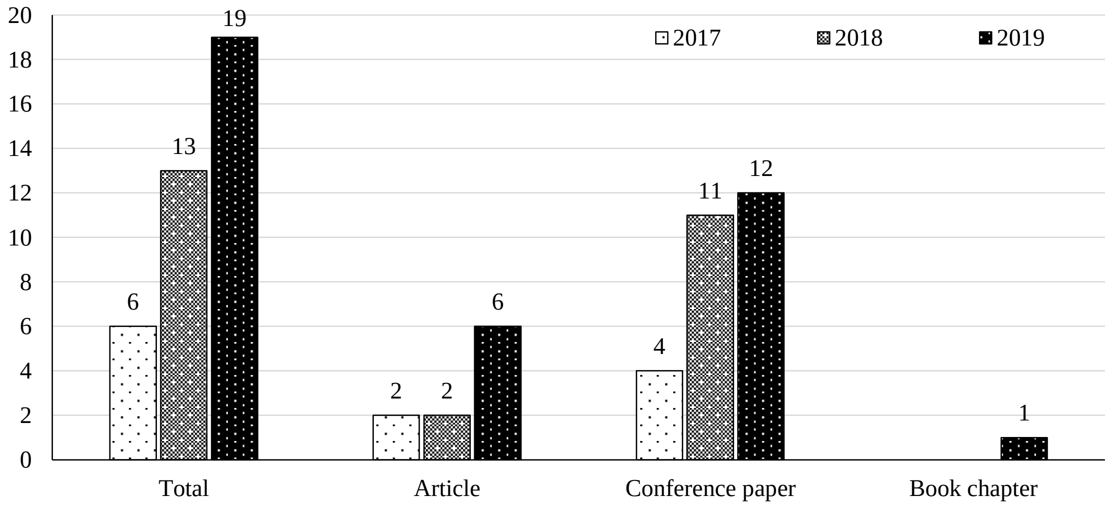

Figure 3. Number and type of publications in recent years.

As you can see, the contributions are all very recent and the trend is strongly growing. The most diffused document type is conference paper (71%), followed by article (26%) and book chapter (3%).

Keywords Statistics

In Figure 4, the most common author keywords are shown. Because the software cannot distinguish between singular and plural or between words with the same route to avoid duplication, we carried out a cleaning phase of the database. We merged most occurrences of words with the same meaning (e.g. "Internet of Things" and "IoT", "smart contract" and "smart contract"). As expected, the most popular keyword was blockchain, used by the authors in 68% of the 55,555 cases, followed by "Internet of Things" (29%) and "smart contracts" (21%), are two topics that are very close to each other.

Geographical Overview

Each publication is attributed to one or more countries, depending on the authors' affiliation. Using the features of VOS viewer, we focused on countries with at least two publications. 11 countries met the threshold. No restriction exists on the number of citations. In Table 1, we show the number of documents and citations for each country.

The United States and China are the countries with the highest labor productivity, followed by India and Italy. However, considering the average number of citations per publication of Spain ranks second in the ranking. Overall, we can say that Europe and Asia are the two most active continents when it comes to blockchain application in the agricultural sector, from a scientific research perspective.

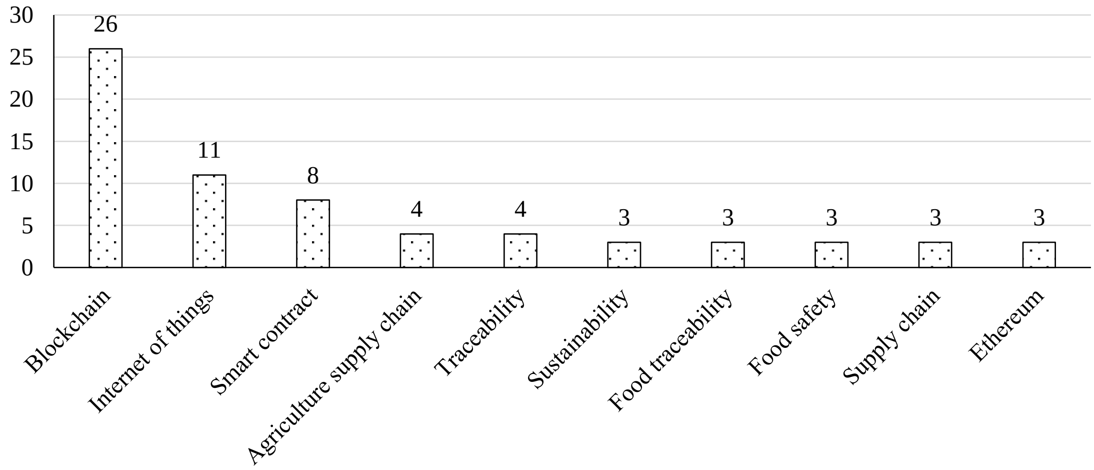

Figure 4. Frequently used author keywords.

Table 1. Number of documents and citations per country.

Country	Number of documents	Number of citations
United States	8	43
China	7	52
India	6	4
Italy	5	21
Spain	3	21
Germany	2	2
United Kingdom	2	1
Australia	2	0
France	2	0
South Korea	2	7
Turkey	2	0

Network Analysis: Research Trends

To identify key search trends, we performed co-occurrence analysis via VOS viewer, choosing "all keywords" as the unit of analysis. We only choose keywords that have at least three occurrences. Out of 435, only 30 keywords reached the threshold of 55,555. However, in this type of analysis, some terms may be duplicated, so we removed the keywords with the lowest number of occurrences, while the meaning remained the same (e.g.: we registered "food traceability", removed "food traceability"). At the end of this cleaning phase, 24 keywords remained. The network of keywords is very useful for identifying the main research trends and the relationships among them. Observe that two nodes of the network are closer than the higher the relative association strength. Given two nodes i and j, let be si and sj respectively the number of occurrences of i and j, and Cij the number of co-occurrences of i and j, then we can define the association strength Asi, j between i and j, as follows [15]:

$$AS\colon \frac{Cj\Gamma}{\text{sijJ} * \text{sj}_{ij}} \qquad (1)$$

In Figure 5, we show the network, results of our analysis.

As expected, the two keywords "blockchain" and "agriculture" are among the most important keywords in the network, as can be seen from the size of the relative nodes, which is proportional to the number appearance. However, looking at other terms on the map can reveal some important search trends.

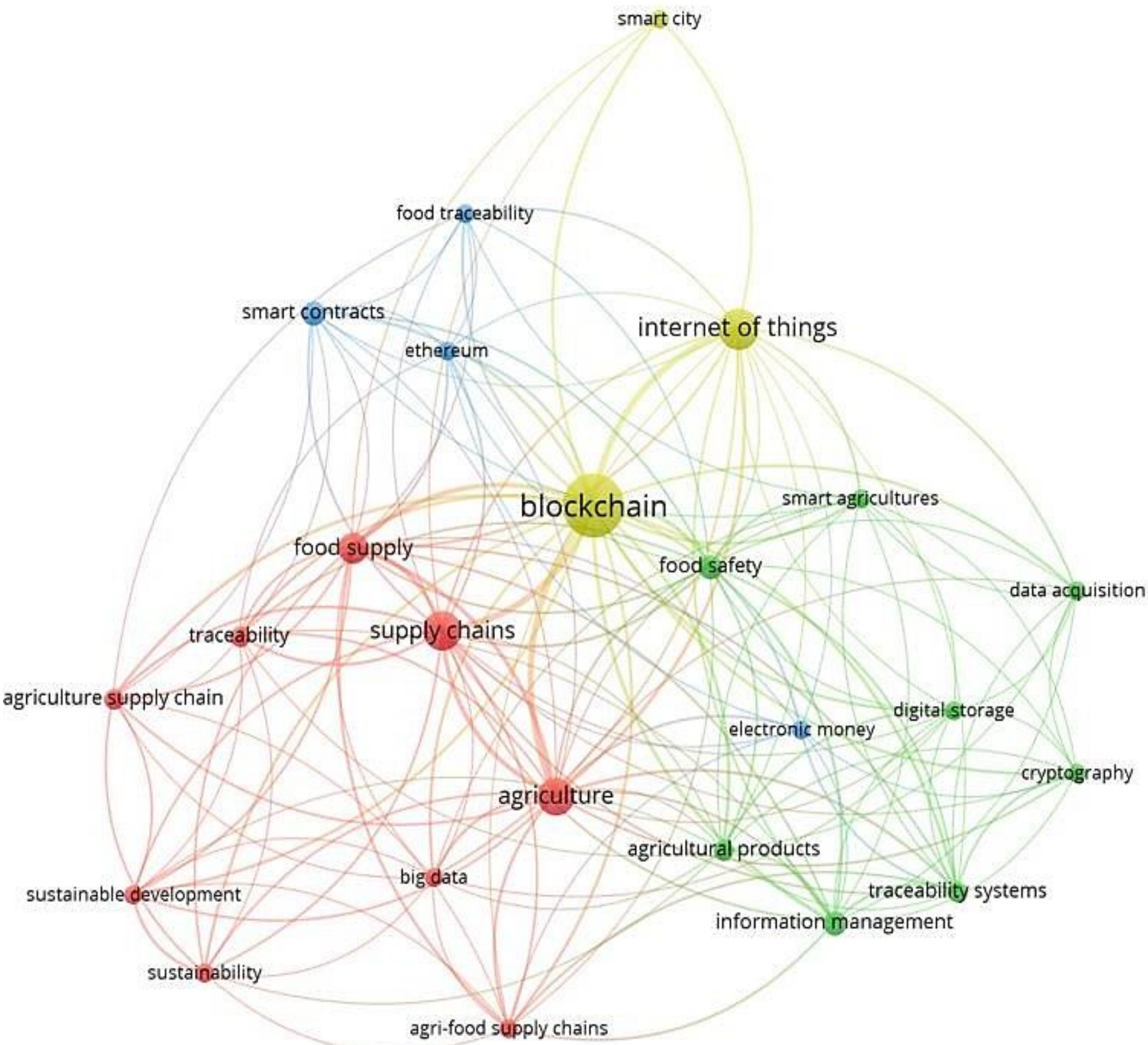

Figure 5. Network of keywords, output of the co-occurrence analysis.

Smart Agriculture

Smart Agriculture can be defined as the application of new technologies (e.g., Internet of Things, Cloud Computing, Global Positioning System, Artificial Intelligence) in traditional agriculture, with the goal of reducing human effort, and increase the use of available resources. The use of sensors, placed in specific areas (e.g., agricultural land), provides real-time information about certain basic variables, such as temperature and humidity. This information is input to artificial intelligence algorithms, which are used to effectively support decision making [12].

Internet of Things (IoT)

IoT is a new paradigm in wireless telecommunications. It is based on things or objects (sensors, mobile phones, RFID tags, etc.), which can interact together to achieve common goals [16].

Sustainability

Several keywords (not all visible in the network, but present in the database, i.e. sustainability, sustainable performance, sustainable development) refer to addressing the sustainability of agricultural supply chains. Agricultural supply chains are among those under the most pressure from activists, policymakers, and consumer organizations, to achieve sustainability standard [17].

Traceability

Traceability can be defined as "the ability to access any information related to what is considered, throughout its life cycle, by means of identification is recorded" [18]. Monitoring the entire supply chain can be accomplished using two main functions: track and trace. Tracking means tracking a product from upstream to downstream in the supply chain; Tracing is rather the reverse process, useful for reconstructing the history of a product (i.e. all the processes it has gone through), using information recorded at each stage of the chain supply [19]. In this context, blockchain can offer a great opportunity by providing consumers with a reliable traceability system, capable of monitoring the entire life cycle of food products.

Ethereum and Smart Contracts

Ethereum is a distributed computing platform based on the open source blockchain and the operating system that supports smart contract functionality. Smart contracts are computer protocols that digitally support contract negotiation.

DATA SELECTION

After the data collection and analysis phase, we focused on one of the research trends discovered: traceability. The blockchain traceability link is quite new and little explored. Among the 38 documents collected, we only select documents that simultaneously meet the following conditions:

- documents written in English.
- documents containing the appearance of one or more words/keys related to traceability: "product traceability", "traceability system", "agricultural product tracking", "food traceability", "traceability", "food traceability system", "traceability information".

Then we get the documents from Table 2, sorted from oldest to most recent.

LITERATURE REVIEW AND DISCUSSION

Below we have reviewed selected articles in detail. Topics addressed, initial problems and contributions are the main information. In the study by Xie *et al*., the focus is on data storage security [20]. The application of blockchain technology to agricultural commodity tracking faces great difficulties in automating data storage and collecting stored hash data. For this reason, the authors propose a dual-chain storage structure, characterized by an on-chain data structure to store the transaction hash of the blockchain and the blockchain itself. The system architecture has three main layers: the sensor layer, the data storage layer, and the application layer.

Table 2. Relevant documents about the application of blockchain in agriculture, for traceability purposes.

Reference	Year	Title	Food area
[20]	2017	Secured data storage scheme based on block chain for agricultural products tracking	General
[21]	2018	Blockchain-based traceability in agri-food supply chain management: a practical implementation	General
[12]	2018	Blockchain and IoT based food traceability for smart agriculture	General
[22]	2018	Blockchain based provenance agricultural products: a distributed platform with duplicated and shared bookkeeping	General
[23]	2019	Blockchain-based soybean traceability in agricultural supply chain	Soybean
[24]	2019	Integrating blockchain, smart contract-tokens, and IoT to design a food traceability solution	General
[25]	2019	Modelling the blockchain enabled traceability in agriculture supply chain	General
[1]	2019	BRUSCHETTA: an IoT blockchain-based framework for certifying extra virgin olive oil supply chain	Olive Oil
[26]	2019	Traceability system of agricultural product based on block-chain and application in tea quality safety management	Tea
[27]	2019	Use of blockchain to solve select issues of Indian farmers	General

The sensor layer has the IoT module, which includes humidity sensor, pressure sensor, temperature sensor, acceleration sensor, global positioning system (GPS) and module general packet radio service (GPRS). The aim is to ensure that data about agricultural products is not altered or destroyed. A demonstration application is used to test and validate the proposed data storage structure under different conditions. IoT-based traceability systems in agricultural supply chains often rely on centralized infrastructure, which can cause serious problems, such as: data integrity, fake, etc. In this context, blockchain is an opportunity to overcome these problems as it allows the creation of decentralized and thrustless systems. To achieve this goal, Agri Block IoT is a fully decentralized traceability system for agri-food supply chain management, integrating IoT devices. It is tested on two publicly available blockchain implementations: Ethereum and Hyperledger Sawtooth. The known farm-to-fork use case is used to evaluate the feasibility of the proposed traceability system. Additionally, the two previously mentioned implementations are compared in terms of: network utilization, latency, and CPU load [21].

Some authors propose another food traceability system based on blockchain and IoT, in which all actors of the smart agricultural ecosystem participate. The system is reliable, open, self-organizing and environmentally friendly. IoT devices are used to reduce human intervention [12]. Two important issues of agricultural traceability systems are: data reliability and integration between information systems of different actors. These problems are addressed by Hua *et al.*, where a distributed peer-to-peer platform is proposed [22]. The authors designed two main structures in the agricultural traceability system: basic plantation information and provenance records. Each basic plantation information record contains typical data of 'a batch of product: identification, species name (i.e. seed name), geographical location, time of planting, company name, greenhouse number, and manufacturer's name; while provenance records are characterized by information about a farm, identity, date, time, location, company, person, farm type, inputs (e.g. name and pesticide quantity), memorandum (i.e., information), and signature number of the company. The proposed platform consists of three roles: subscription center, data node, and user. There are two types of users: the first type uploads data and must be registered on the subscription center, the second type is a public user (i.e. end user), who can query the node data. The two problems mentioned above have been resolved because once data is included in the platform, it cannot be modified anymore. Furthermore, all stakeholders are involved from the beginning, so there are no issues with incompatibilities in data structures. The potential of the Ethereum blockchain and smart contracts is exploited by Salah *et al.* to track and trace the soybean supply chain [23]. The proposed framework allows for transactions without the need for intermediaries or infrastructure. The authors explain in detail: system architecture, entity relationship diagram, sequence diagram, and algorithms based on blockchain-based approach. Overall, the proposed solution has many common aspects and can therefore be used not only for soybeans but also in many other agricultural supply chains. This results in the following benefits: integrity, security, and reliability. Harvest Network is a theoretical food traceability application that integrates Ethereum blockchain and IoT, uses GS1 protocol and smart contracts. With the aim of making agricultural supply chains more transparent, the Kim *et al.* proposed "food bytes", a data structure that allows consumers to be fully informed about the origin of food as final product [24].

Further research identifies and analyses 13 enablers for the adoption of blockchain technology in agricultural supply chains: anonymity and security, auditability, decentralized database, immutability, advanced risk management, provenance, reduced transaction costs, reduced settlement time hours, secure database, smart contracts, traceability, and transparent accounting. First, they are validated by several experts, then the relationship between them is found using the following two methods: Interpretive Structural Modelling (ISM) and Evaluation Laboratory and decision-making test (DEMATEL). As a result, traceability of agricultural products is the most important enabler [25]. Instead, BRUSCHETTA is a blockchain-based IoT application for traceability and certification of the extra virgin olive oil (EVOO) supply chain, presented by Arena *et al.* [1]. EVOO is one of the most valuable Italian products and is generally susceptible to scams. The proposed framework allows tracking of the entire chain so that consumers can access, even using a smartphone, all information about the following stages: growing, harvesting, manufacturing, packaging, storage, and transportation. Simulation-based performance evaluation is performed to measure the storage time of a new value on the blockchain, in different settings. Considering that the results show that the considered system is not always suitable for real industrial scenarios, a dynamic self-regulation mechanism is proposed. In the study by Liao and Xu, a blockchain-based traceability system for tea quality and safety is proposed [26]. The framework has three main layers: data layer, business logic layer, and presentation layer. The data layer uses the Ethereum blockchain and a relational database, built through MySQL. The end consumer can scan the product's QR code and get all the information before purchasing the tea. The retrieved information is verified using blockchain technology to evaluate its authenticity. Blockchain technology and commodity trading platforms are essentially combined with the aim of increasing the reliability and security of the entire system. Instead, a blockchain-based mobile application is proposed by Yadav and Singh to address some specific problems of Indian farmers, identified through an extensive literature review and application of engineering techniques [27]. The mobile application includes three modules: traceability, smart contract-based monitoring, and information system. According to the authors, the use of blockchain technology in the agricultural sector in India can lead to a significant increase in the quality of products offered to consumers, thereby leading to the sustainable development of country.

Discussion

Despite the rapid increase in scientific contributions related to blockchain applications in several contexts, it can be said that, when it comes to the agricultural sector, this technology is still in its infancy. Especially on the issue of food traceability, very few articles have been reported in the literature. In Table 3, we show: (1) the main problems of current technology in tracking and tracing agricultural supply chains, and (2) how the use of blockchain technology can solve them.

As shown in Table 3, despite the efforts that have been made over the past decades in the field of food traceability, many limitations still exist and can be overcome by applying blockchain technology [28, 29]. However, there are certain aspects that remain unexplored in the literature which we can call open research questions (ORQs). They identify future challenges:

- *ORQ-1: What is the economic and organizational impact of blockchain applications on real agricultural supply chains?*
  In the literature, there is still a lack of research on the differences before and after implementing blockchain technology in actual agricultural supply chains. Many articles are quite general and

limited to simulating the applicability of this breakthrough technology. The use of real case studies could be very useful to better estimate costs, benefits, and socio-organizational impacts. Therefore, empirical data is really needed. Some studies even describe this technology as "deskilling" for workers, due to automation of procedures and elimination of third-party intermediaries [30], but it would be very interesting to have quantitative feedback about this statement.

- *ORQ-2: What is the relationship between blockchain and IoT, in terms of data management?*
  Almost all the studies we analyzed propose an integration between blockchain and IoT. However, IoT generates a large amount of data, then the production speed of block and transactions could be not enough to guarantee traceability; in this context, blockchain can be seen as a limited resource and the data storage schemes need to be revised and improved [20]. Further research is needed to clarify the feasibility of blockchain-IoT integration.
- *ORQ-3: How ready are stakeholders in the agricultural supply chain to adopt public/permission less blockchain?*
  Opening a blockchain-based platform can be a significant limitation, as anyone on the network can view data. This means that confidential data is accessible to everyone (e.g. trade secrets). On the one hand, if the benefits of this technology seem clear in the literature, there is a lack of research on the actual trends in which different actors in the chain might have to adopt it. It would be helpful to send some questions to farmers, transporters, wholesalers, to understand what they think about this technology. In this context, other important related questions need to be answered: Are the stakeholders mentioned above willing to change the way they carry out certain activities? Are they ready to use mobile devices to exploit the potential of IoT?

Table 3. Main problems of current technologies in tracking and tracing agricultural products, and blockchain contribution.

Issue	Blockchain contribution
Many IoT-based traceability systems for agricultural supply chains are based on centralized infrastructures, which lead to the following issues: data integrity, tampering, and single points of failure [21]	A verified and validated data remains permanently stored in the blockchain [20]. Alteration of the database on a single node of the blockchain is not possible, so, stability and reliability are guaranteed [20]. The blockchain technology eliminates the need for a third party or an intermediary, responsible for controlling the system. In fact, based on a transparent consensus mechanism, it ensures the execution of only valid transactions [28]. All the operations are visible to the nodes of the network, so, the participants' malicious actions are avoided [25]
Many traditional logistic information systems in agri-food supply chains track and store orders and deliveries, but neglect these features: transparency, traceability, auditability [29]	All the operations are visible to the nodes of the network, so, the participants' malicious actions are avoided [25]. All the records stored in a blockchain are based on a consensus reached by most of the peers in the network. Therefore, the distributed ledger is immutable and transparent [21]
Information asymmetry among the different stakeholders in current food supply chains [24]	Inserting data into a public blockchain ensures full transparency.
Consumers live in an asymmetric food information environment, so, they cannot access the information about the whole agricultural supply chain [26]	The data is accessible in real-time, and the consumer can fully retrieve the information about the processes that the product, which is on the shelf, has undergone [24]
Lack of standardization in data format. There is no common agricultural protocol shared among the actors [24]	Blockchain is a single platform, shared among all the participants, then there are no data incompatibility problems

- *ORQ-4: How to ensure the authenticity of data entered the blockchain?*
  It is known that authenticity and transparency are among the undisputed characteristics of this technology. However, few studies have investigated the issue of possible recording of erroneous data (i.e. fraud). In essence, a related party can commit fraud. Of course, blockchain technology

will help uniquely identify the fraudster, in case of fraud detection. But how can you avoid fraud in the first place? Some proposals are contained in the document: penalties for dishonest farmers, use of hardware camera to take pictures and send them to the blockchain [23]. However, this branch of research should be better explored as it significantly relates to the overall reliability of blockchain technology.

CONCLUSION

In this work, a review of the literature about the application of blockchain technology in the agricultural sector with a focus on food traceability issues was carried out, to detect: (1) the current research trends, (2) the most significant issues that blockchain could solve in agricultural supply chains, and (3) the future challenges or open research questions. The results of the use of a three-steps research methodology showed that this technology is strongly growing, given the very high number of scientific contributions published in recent years; however, with reference to the agricultural sector, it can still be considered in its early stage: there is an almost total absence of real case studies, so, it is currently not clear how an agricultural supply chain can obtain benefits from an economic and organizational point of view through the implementation of a real blockchain-based platform. Furthermore, it would be necessary to deepen the potential propensity of stakeholders towards the adoption of this technology; substantially, much effort is still needed to increase the credibility and reputation of blockchain. Most of the scientific documents recently published are conference papers and this confirms that this topic was of great interest at the last scientific conferences. The network analysis provided using the VOS viewer software and based on the study of the most widely used keywords, highlighted some research trends that go hand in hand with the impetuous rise of the blockchain: smart agriculture and internet of things are the main ones. Using an appropriate set of traceability-oriented keywords, it was found that, on Scopus, there were only the top 10 articles, where chain tracking and tracing models proposed agricultural supply, exploiting the potential of blockchain technology. They were scrutinized, emphasizing three primary elements: the initial problem, the field of interest, and the contribution. Most of them involve concepts that are too general and not closely related to actual specific agricultural supply chains. Overall, blockchain looks very promising and the high number of contributions announced in recent months confirms the scientific community's interest in this technology which, soon, could is a valid way to reduce fraud and errors in the agricultural supply chain.

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