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Blockchain and agricultural supply chains traceability: research trends and future challenges

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Abstract

Blockchain is today one of the most interesting and debated research topics. Blockchain technology was implemented for the first time in the financial sector a few years ago. However, it is currently used in many other areas, such as: healthcare, smart cities, smart contracts, energy markets, government sector. The success of this technology mainly lies in the following properties: reliability, transparency, immutability. In this study, we collect and analyze the main contributions in the literature about the application of blockchain in the agricultural sector, focusing on food traceability issues. Considering the quick growth of this technology and the high number of published documents in recent months, there is a need to catalog the different methodologies, proposed by the various scholars. Our aim is to detect the current research trends and possible future challenges. In the agricultural context, the need for an adequate traceability system is motivated by several bad habits and problems, such as the wide use of pesticides and fertilizers in fruits and vegetables, which are extremely harmful for human health. Moreover, in the last few years, the consumers' attention about the quality of agricultural products has considerably increased. The present study shows that the blockchain technology is still in its early stage. Although there are several proposals in the literature, still a limited number of applications have been put into use in the real context. From the point of view of scientific research, only some countries are investing in this technology: China and United States are among the most active, but Italy is also very involved in this phenomenon. Overall, the blockchain technology appears very promising, but still many efforts are needed to reach the maturation stage.

Keywords: Blockchain; Literature Review; Agricultural Supply Chain; Food Traceability; Internet of Things

1. Introduction

Blockchain is today one of the most interesting and debated research topics. A blockchain can be defined as "an immutable ledger for recording transactions, maintained within a distributed network of mutually untrusted nodes. A blockchain is a list of ordered blocks, where each block stores a variable-size list of transactions" [1]. The first blockchain was introduced by Satoshi Nakamoto, who proposed the concept of Bitcoin cryptocurrency in 2008. This famous and recognized application of the blockchain in the financial field allowed the exchange of digital money within an untrusted network of anonymous nodes, without a third-party intermediary (i.e. a central bank) [2]. However, the blockchain technology is currently used in many other sectors, such as: healthcare [3,4], smart cities [5], smart contracts [6,7], energy markets [8], government [9]. The success of this technology mainly lies in the following properties: reliability, transparency, immutability.

In this paper, we focus on the application of the blockchain in the agricultural supply chains for ensuring food traceability. An agricultural supply chain can be defined as a set of actors involved in farming, distribution, processing and marketing of agricultural and horticultural products, "from field to table" [10]. Food traceability is today a topic of great importance and numerous frameworks were introduced in the literature in recent decades for avoiding the occurrence of food scandals such as those occurred in the past. However, the blockchain-food traceability link is very new and still quite unexplored. Food traceability is a regulatory provision, even if with slightly

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different characteristics depending on the geographical area [11].

In the agricultural context, the need for a traceability system is motivated by a multitude of bad habits and problems. First of all, the widespread use of pesticides and fertilizers in fruit and vegetables, which lead some residues in the final product, very harmful for human health. Hormones and other substances, heavily used in the cultivation phase, serve to reduce maturation time and consequently increase field yield. In some cases, mineral oil is even used to brighten biscuits and rice. All these practices, not only reduce the nutritional value of the agricultural product, but also represent a strong risk for consumers' safety [12].

The main purpose of this paper is to review the literature about the applications of the blockchain in the agricultural supply chains, focusing on food traceability issues. To the best of our knowledge, this is the first review, which deeply explores the link between blockchain and food traceability, in the agricultural context. For completeness of information, there is also another review [13] regarding blockchain and agriculture, but is more general than this in terms of topics covered, not being focused on food traceability. Moreover, considering the very quick growth of the blockchain and the high number of contributions published in recent months, there is a need to collect, catalog and classify the different proposed methodologies, with the aim of understanding research trends and possible future developments or challenges. We collected the studies till September, 2019.

The paper is structured as follows. In Section 2, the research methodology, used for conducting the study, is described. Sections 3-5 respectively correspond to the implementation of the three steps of the methodology. In Section 6, the conclusions are presented.

2. Research Methodology

Our research methodology is characterized by the following steps:

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

The first phase concerns the collection of scientific papers using appropriate keywords. These contributions are analyzed in order to highlight the following quantitative aspects: number of papers and relative citations per year, document type, geographical location of the authors, keywords statistics, research trends. This step is partly supported by the free software VOSviewer (version 1.6.13), which can create and visualize bibliometric networks [14].

In the second phase, we focus on a subset of the research trends identified and we consistently select the scientific articles of interest, according to some inclusion/exclusion criteria (e.g., language of the paper).

In the last phase, the selected papers are reviewed. Then, a discussion about problems, research trends, future developments and/or challenges is provided.

3. Data collection and analysis

The dataset for this study was created using Scopus, at the end of September, 2019. Scopus is one of the main and most recognized databases of scientific research. First of all, the term "blockchain" was used as search key in the "document search" of Scopus, in order to have a general and quantitative overview about this phenomenon. In Figures 1-2, we show respectively the number of published papers and the number of citations per year, on the period 2013-2019, excluding the following document types: "Conference Review", "Note", "Editorial".

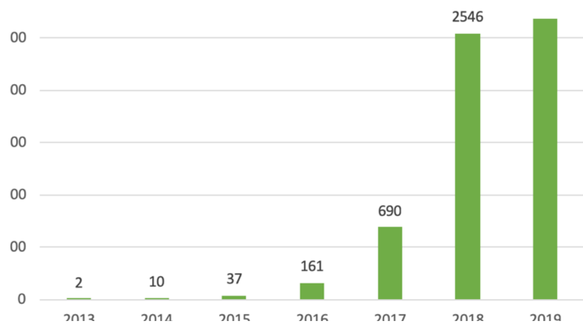

Fig. 1. Number of published papers per year about blockchain topic, on the period 2013-2019

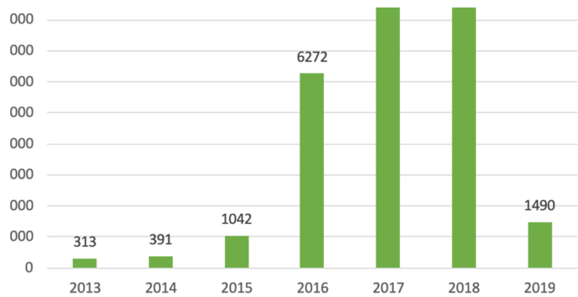

Fig. 2. Number of citations per year about blockchain topic, on the period 2013-2019

It can be noted that the very first contributions about blockchain date back to the 2013-2014 period. However, the real explosion was recorded on the three-year period 2016-2018, a historical moment in which this technology had a strong expansion in several contexts. The expected trend for 2020 appears to be very promising, considering that over 100 articles have already been published.

However, the present study focuses on the link blockchain-agriculture, then we subsequently updated the research key in the "document search" of Scopus: "blockchain AND agriculture". Using the same exclusion conditions, above-mentioned, in this case we obtained only 38 results. This low number is really important because it indicates how new the research branch, we examine in this study, is. In the following subsections, we analyze these 38 papers, using VOSviewer.

3.1. Publications: number and type over the years

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

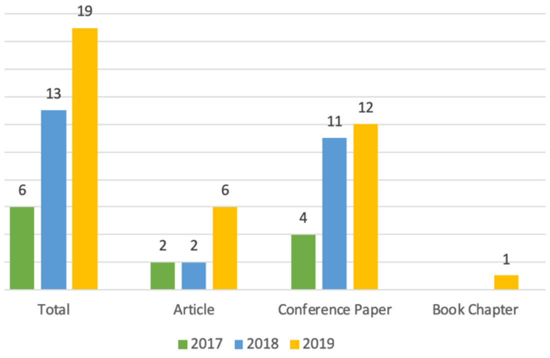

Fig. 3. Number and type of publications in recent years

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%).

3.2. Keywords statistics

In Figure 4, the most common author keywords are showed.

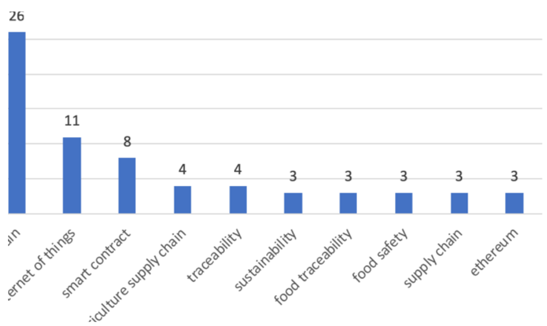

Fig. 4. Frequently used author keywords (count≥3)

Since the software cannot distinguish the difference between singular and plural or between words having the same root, in order to avoid duplication, we made a cleaning phase of the database. In particular, we merged the occurrences of words having the same meaning (e.g., "internet of things" and "iot", "smart contract" and "smart contracts"). As expected, the most diffused keyword is blockchain, used by authors in 68% of cases, followed by "internet of things" (29%) and "smart contract" (21%), which are two topics very close to blockchain.

3.3. Geographical overview

Each publication was assigned to one or more countries, depending on the authors' affiliations. Using the VOSviewer functionalities, we focused on the countries, having at least two publications. 11 countries met the threshold. No constraints were on the number of citations. In Table 1, we show the number of documents and citations per each country.

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

United States and China are the most prolific countries, followed by India and Italy. However, if we consider the average number of citations per publication, Spain holds the second place of the ranking. Overall, we can say that Europe and Asia are the two most active continents about the application of blockchain in the agricultural sector, from the point of view of scientific research.

3.4. Network Analysis: research trends

With the aim to identify the main research trends, we made a co-occurrence analysis through VOSviewer, choosing as unit of analysis "all keywords". We selected only the keywords with at least three occurrences. Out of 435, only 30 keywords met the threshold. However, in this kind of analysis some terms could be duplicated, therefore we removed the keywords with the lowest number of occurrences, when the meaning was the same (e.g. we saved "food traceability", removing "food traceabilitys"). At the end of this cleaning phase, 24 keywords remained. In Figure 5, we show the network, output of our analysis.

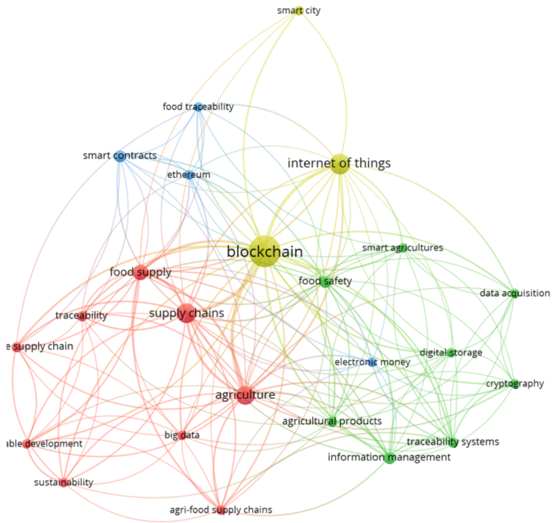

Fig. 5. Network of keywords, output of the co-occurrence analysis

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 the higher the relative association strength. Given two nodes i and j, let be S_i and S_j respectively the number of occurrences of i and j, and $C_{i,j}$ the number of co-occurrences of i and j , then we can define the association strength $AS_{i,j}$ between i and j, as follows [15]:

$$AS_{i,j} = \frac{C_{i,j}}{S_i * S_j} \quad (1)$$

As expected, the two keywords “blockchain” and “agriculture” are among the most important in the network, as can be seen from the size of the relative nodes, which is proportional to the number of occurrences. However, looking at the other terms in the map, some important research trends can be detected.

Smart Agriculture: smart agriculture can be defined as the application of the new technologies (e.g., Internet of Things, Cloud Computing, Global Positioning System, Artificial Intelligence) into traditional agriculture, with the aim of reducing human effort and increasing the use of available resources. The use of sensors, placed in particular areas (e.g., farmland), gives real-time information about some fundamental variables, such as temperature and humidity. This information is the input of artificial intelligence algorithms, used for efficiently supporting 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 with each other 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) address the agricultural supply chain sustainability. Agricultural supply chain is among the most subjected to the pressure of activists, policy makers, and consumer organizations, for achieving sustainability standards [17].

Traceability: traceability can be defined as “the ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications” [18]. The monitoring of the whole supply chain can be obtained using two main functions: tracking and tracing. Tracking means following a product by upstream to downstream within the supply chain; tracing is instead the reverse process, useful for reconstructing the history of a product (i.e., all the processes it has undergone), by means of information recorded at each step of the supply chain [19]. In this context, blockchain can represent a big opportunity for giving consumers a trusted traceability system, able to monitor the whole lifespan of food products.

Ethereum & Smart contracts: Ethereum is an open source, public, blockchain-based distributed computing platform and operating system, which supports smart contract functionality. A smart contract is a computer protocol, which digitally facilitates the negotiation of a contract.

4. Data selection

After the phase of data collection and analysis, we focused on one of the detected research trends: traceability. The blockchain-traceability link is quite new and little explored.

Out of the 38 collected papers, we selected only those, which simultaneously met the following conditions:

- documents written in English
- documents having the occurrence of one or more keywords related to traceability: “product traceability”, “traceability systems”, “agricultural products tracking”, “food traceability”, “traceability”, “food traceability systems”, “traceability information”

Then, we obtained the documents in Table 2, ordered from the oldest to the newest.

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	Modeling 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	Extra-Virgin 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

5. Literature review and discussion

Below, we reviewed into the detail the selected papers. Topic covered, starting problem and contribution are the main information reported.

In [20], the focus is on the security in data storage. The application of blockchain technology for tracking agricultural products involves an enormous difficulty in automating data storage and obtaining hash data stored. For this reason, the authors propose a double-chain storage structure, characterized by: a chained data structure for storing the blockchain transaction hash, and the chain of the blockchain itself. The system structure has three main layers: Sensing Layer, Data Storage Layer, Application Layer. The Sensing Layer has an IoT module, which includes: humidity sensor, pressure sensor, temperature sensor, acceleration sensor, Global Positioning System (GPS) and General Packet Radio Service (GPRS) modules. The aim is to ensure the data on agricultural products are not tampered or destroyed. A demo application is used for testing and validating the proposed data storage structure under different conditions.

IoT-based traceability systems in agricultural supply chains often rely on centralized infrastructures, which can cause some important problems, such as: data integrity, tampering. In this context, blockchain is an opportunity to overcome these issues because it makes possible the creation of decentralized trustless systems. To this aim, AgriBlockIoT is a fully decentralized traceability system for the agri-food supply chain management, which integrates IoT devices. It is tested on two publicly available blockchain implementations: Ethereum and Hyperledger Sawtooth. The known from-farm-to-fork use-case is used for assessing the feasibility of the proposed traceability system. Moreover, the two previous mentioned implementations are compared in terms of: network usage, latency, and CPU load [21].

Some authors propose another food traceability system based on blockchain and IoT, where all the actors of a smart agriculture ecosystem are involved. The system is trusted, open, self-organized and ecological. The IoT devices are used for reducing human intervention [12].

Two important issues of agricultural traceability systems are: the reliability of the data and the integration between information systems of different actors. These are solved in [22], where a distributed peer-to-peer platform is proposed. In particular, the authors design two main structures in the agriculture traceability system: basic planting information and provenance record. Each record of basic planting information contains the typical data of a batch of product: identity, name of species (i.e., seed name), geographical location, planting time, company name, greenhouse number, grower's name; while a provenance record is characterized by the information about an agricultural operation, then: identity, date time, location, company, person, operation type, inputs (e.g., name and quantity of pesticides), memo (i.e., additional information), digital signature of the company. The proposed platform includes three roles: registration center, data nodes, and users. There are two categories of users: the first ones upload the data and need to be registered on the registration center, the second ones are the consumer users (i.e., the end users), who can query the data nodes. The two issues above mentioned are solved because the data, once inserted in the platform, can no longer be modified; moreover, all the actors are involved from the start, then there are no incompatibility problems in the data structure.

The potentials of the Ethereum blockchain and smart contracts are exploited in [23] for soybean supply chains tracking and traceability. The proposed framework allows transactions execution, without intermediaries or trusted centralized authorities. The authors explain into the details: the system architecture, the entity-relation diagram, the sequence diagram and the algorithms, on which the blockchain-based approach is based. Overall, the proposed solution has many general aspects, then can be used not only for soybean, but also in many other agricultural supply chains. It leads to the following advantages: integrity, security, and reliability.

Harvest Network is a theoretical food traceability application, which integrates the Ethereum Blockchain and IoT, using GS1 protocol and smart contracts. With the aim of making more transparent the agricultural supply chain, the authors of [24] propose "food bytes", a data structure, which allows the consumers to be fully informed about the origin of the final product.

Another research work identifies and analyzes 13 enablers for the adoption of the blockchain technology in agricultural supply chains: anonymity and privacy, auditability, decentralized database, immutability, improved risk management, provenance, reduced transaction costs, reduced settlement lead times, secured database, smart contracts, traceability, transparency. They are first validated by some experts, then the relationships between them are found, using the two following methodologies: Interpretive Structural Modelling (ISM) and Decision-Making Trial and Evaluation Laboratory (DEMATEL). The output is that the traceability of the agricultural products results the most important enabler [25].

BRUSCHETTA is instead a blockchain-based IoT application for traceability and certification of an Extra-Virgin Olive-Oil (EVOO) supply chain, presented in [1]. EVOO is one of the most valuable Italian products and is typically very prone to fraud. The proposed framework allows to trace the whole chain, so that the consumer can access, even using a smartphone, all the information about the following steps: farming, harvesting, production, packaging, storage, and transport. A simulation-based performance evaluation is carried out, in order to measure the storing time of a new value on the blockchain, under different settings. Considering that the results show that the considered system is not always suitable in real industrial scenarios, a mechanism for dynamic auto-tuning is proposed.

In [26], a blockchain-based traceability system for tea quality and safety is proposed. 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 final consumer can scan the QR code of the product and retrieve all the information before buying tea. The retrieved information is verified using the blockchain technology, in order to assess its authenticity. Substantially, blockchain technology and product trading platform are combined, with the aim to increase reliability and safety of the whole system.

A blockchain-based mobile app is instead proposed in [27] for solving some select issues of Indian farmers, identified through a deep literature review and the application of the Delphi technique. The mobile app includes three modules: traceability, smart-contract based monitoring, and information system. According to the authors, the use of the blockchain technology in the agricultural sector in India, could lead to a significant increase in the quality of the products offered to the consumers, therefore to a sustainable development of the country.

5.1. Discussion

Despite the recent proliferation of scientific contributions related to the application of the blockchain in several contexts, we can say that, if we refer to the agricultural sector, this technology is still in its early stage. In particular, about food traceability issues, very few papers are present in the literature.

In Table 3, we show (1) the main problems of the current technologies in tracking and tracing agricultural supply chains and (2) how the use of blockchain technology could solve them.

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, then 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, then 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 records stored in a blockchain are based on a consensus reached by the majority 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] Consumers live in an asymmetric food information environment, then they cannot access the information about the whole agricultural supply chain [26]	Inserting data into a public blockchain ensures full transparency. 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] The different stakeholders in the agricultural supply chains have their own data recording and traceability systems. This leads to a dangerous incompatibility among software and data structure, then to the impossibility to completely guarantee food traceability [22]	Blockchain is a single platform, shared among all the participants, then there are no data incompatibility problems

As shown in Table 3, despite the efforts made in the last few decades in the field of food traceability, many limits still remain and can be overcome, by adopting the blockchain technology.

However, there are some aspects still little explored in the literature, which we can name open research questions (ORQs). They determine the future challenges:

- ORQ-1: *What is the economic and organizational impact of the blockchain application on a real agricultural supply chain?*
  In the literature, there is a lack of studies about the differences before and after the implementation of the blockchain technology in real agricultural supply chains. Many papers are quite general and limited only to simulate the possible application of this disruptive 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 studies are needed to clarify the feasibility about blockchain-IoT integration.

- ORQ-3: *How willing are the stakeholders of an agricultural supply chain to adopt a public/permission-less blockchain?*
  The openness of a blockchain-based platform could be a significant limit because the data can be viewed by anyone in the network. This means that also confidential data (e.g., trade secrets) may be available to anyone. While on the one hand, the benefits of this technology appear to be clear in the literature, there is a shortage of studies on the actual propensity that the various actors of the chain could have in adopting it. The submission of some questionnaires to farmers, carriers, wholesalers, would be very useful to understand their thinking about this technology.
  In this context, other important related questions need to be answered: are the above-mentioned stakeholders willing to change the way they perform certain activities? Are they willing to use mobile devices for exploiting the potentials of IoT?

- ORQ-4: *How to guarantee the truthfulness of the data entered in the blockchain?*
  It is well known that authenticity and transparency are among the undisputed properties of this technology. However, few studies have investigated the problem of the possible record of wrong (i.e., fraudulent) data. Substantially, it is possible that a stakeholder can cheat. Of course, the blockchain technology would allow the cheater to be uniquely identified, in the event of fraud detection. But, how to avoid fraud from the beginning? Some proposals are present in the literature: penalties for dishonest farmers, use of hardware cameras, which take images and send them to the blockchain [23]. However, this research branch should be better explored because it significantly concerns the overall credibility of the blockchain technology.

6. Conclusions

In this research 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, in order to detect: (1) the current research trends, (2) the most significant issues that blockchain could solve in agricultural supply chains, (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, then 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 in the last scientific conferences. The network analysis provided through the use of the VOSviewer 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 adequate set of traceability-oriented keywords it was found that, on Scopus, there are only ten main articles, in which models for track and trace the agricultural supply chains were proposed, exploiting the potentiality of blockchain technology. They have been reviewed, highlighting three main aspects: starting problem, area of interest, and contribution. Most of them concern too general concepts and are not strictly related to a specific real agricultural supply chain.

Overall, blockchain appears very promising and the high number of contributions published in recent months confirms the scientific community's interest in this technology, which in the near future may be a valid means to minimize fraud and errors in the agricultural supply chains, increasing quality and safety of food products.

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