Blockchain technology for cybersecurity applications in the food supply chain: A systematic literature review

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Abstract: The food supply chain is a complex system responsible for the circulation of food products, and managing it requires IT infrastructures and technologies that are free of cyber-risk and that are used to connect, build and share information. Blockchain technology is a distributed ledger that can play an important role in providing data transparency, trust, immutability, integrity, and traceability to all food supply chain members. The purpose of this review is to depict a landscape of the scientific literature enriched by an author's keywords analysis to develop and test blockchain's capabilities for cyber-risks prevention in international food supply chains. This paper combines a systematic literature review (SLR) process with the analysis of bibliographic networks. Papers from interdisciplinary areas published between 2016 and 2020 were selected to review the evolution of cyber-risks, cybersecurity solutions, and blockchain solutions used as a reference to identify, classify and specify requirements for a cyber secure distributed ledger. The findings show how blockchain technology needs other technologies, such as advanced ICT and Internet of Things (IoTs), for better food product traceability, safety, and transparency. It shows the multiple choices of blockchain architectures and their maturity level to interface with ICTs and IoTs. Based on the analysis of literature, research gaps, and future research directions are proposed in this paper regarding the applications of blockchain technology for managing cyber risks in the food supply chain. To the best of our knowledge, this paper provides an important contribution of literature with an SLNA entirely focused on the intersection between cyber-risks, blockchain and food supply chains that are continuously evolving, and shaping new supply chain models.

Keywords: Blockchain technology, Cyber risks, Cybersecurity, Food supply chain, Systematic literature review

1. Introduction

The food chain worldwide involves multi-stakeholders with many different actors, such as farmers, processors, wholesalers, retailers, distributors, and consumers (Caro *et al.*, 2018). Raw and organic materials are used by primary producers to produce crops and livestock. The packaged and labelled items are released for the distribution phase and delivered to the retailers where the consumer is the end-user of the chain (Malik, *et al.*, 2018).

The fragility of global food supply chains is increasing due to cyber-risks that directly or indirectly endanger the stability and security of society. Cyber risks are not different from the safety risks that food companies are dealing with every day. The same methods applied to recognize and resolving the risks associated with food production and processing can be extended to data security. These methods include assessment of the risks and the likelihood of incidents and the development of mitigation programs. Certainly, beginning with a definition of cyber risks can be useful. As stated by Boyes, "A cyber - event is any disturbance to this interdependent network that leads to loss of functionality, connectivity, or capacity" (Boyes, 2015). The vulnerability of the food supply chain is evidenced by cyber–attacks, such as companies engaged in counterfeiting, theft, food fraud, data manipulation, or falsification. The potential consequences of cyber-attacks are massive financial losses; for instance, it has been reported that there was an average cost of 3 million Euro for each cyber-attack on Italian companies' data in 2018 (Resilience360, 2018). In the 1990s and 2000s, food industries were focused on the advent of new computers and information technologies for revolutionizing the industrial control systems (ICSs) applied in food processing and manufacturing, and operations research methods started playing a role in network survivability, intrusion detection, countering denial of service attacks, risk assessments, limiting access to confidential data, legitimate access, and so on (Wright, *et al.*, 2006). However, these new technologies come with new risks, such as malicious software and users threatening the safety of goods, customers, and brand image of companies and also new solutions with the components of the 4th industrial revolution, i.e., Internet of things, Cyber-Physical Systems, Physical Internet and Automation. In this vein, as a potential solution to mitigate the aforementioned issues, academic institutions and practitioners have recently conducted several theoretical and practical projects with blockchain technology for integrity data and systems, transparency, safety, and security (Aceto, 2019; Kshetri, 2017). "The blockchain is a new organizing paradigm for the discovery, valuation, and transfer of all quanta (discrete units) of anything, and potentially for the coordination of all human activity on a much larger scale than has been possible before" (Swan, 2015). Researchers have extended their interest in blockchain applications in the food sector,

mainly with a rapid increase in the contribution of scholarly specialists for traceability of products (Tian, 2016; Caro *et al*, 2018; Kamble *et al.*, 2019). However, none of the studies addresses the application of the blockchain technology in cyber food supply chain risk management. Moreover, blockchain technology applied in the food supply chain seems to be an interesting research stream for future studies.
Following on from the above discussion, to the best of our knowledge this study is the first paper entirely focused on the intersection between cyber-risks, blockchain, and food supply chains and attempt to seek information that is characterized by a systematic literature network analysis (SLNA) using bibliometric tools, namely, the analysis of the citation network and the analysis of the author's keywords co-occurrence network. These tools are quantitative-based methods that have been used to analyse literature in several contexts, such as supply chain, smart factory, and blockchain (Strozzi *et al.*, 2017; Zhao *et al.*, 2019).
This paper provides a contribution of literature on two-fold. First, three main streams were identified: one stream devoted to the use of blockchain for assuring traceability and authenticity in the food supply chain; the other one referred to maturity of blockchain technology in agriculture and food supply chains and finally, the third stream examines industrial applications of blockchain technology. Second, this systematic review also sheds light on different research areas such as emerging technologies applications in sustainable and transparent food supply chain, different architectures of blockchain in combination with smart contracts, IoT, and edge computing, blockchain's role as a solution for privacy and security challenges, and traceability database systems to ensure food safety and security.
The rest of the paper is structured as follows. In section 2, the research methodology is presented. Then, section 3 is devoted to the results of the SLR methodology. Section 4 contains the bibliometric review. Conclusions, the research gaps, and proposed future research directions are presented in section 5.

2. Research methodology

A systematic literature network analysis (SLNA) is chosen to extract and analyse the papers. The procedure consists of two methods: systematic literature review (SLR) and citation network analysis (CNA).
In the initial stage, a systematic literature review (SLR) was conducted through research questions to have a high-quality literature review by adapting key features (Denyer and Tranfield, 2009). Secondly, the literature was identified in Scopus. Thirdly, literature selection was done, based on an explicit criterion to include and exclude papers and evaluations. A collection of selected papers will be the product of this process. The software VoSviewer (http://www.vosviewer.com) was used to create bibliometric networks and, in this study, was applied to study author keywords analysis (Van Eck and Waltman, 2009). Pajek (De Nooy *et al.*, 2011) is another software for social network analysis, and, in this study, it was applied for creating, visualizing, and exploring citation networks.

3. Systematic literature review

3.1 Questions formulation

The formulation of the questions is the following, given that we would like to understand the role of the blockchain in the cybersecurity of the food supply chain:
RQ1: What are the potential cyber risks in the food supply chain?
RQ2: How can blockchain solutions identify potential cyber risks?

3.2 Identify the literature

All the search terms and their combinations were searched in the full document of title, abstract, and keywords on Scopus, the largest database of scientific peer-reviewed literature. A set of different synonyms of "Blockchain" and "food supply chain" was created in Scopus and then confirmed by a team of academics and production managers. Database research string was obtained in the following: (TITLE-ABS-KEY("blockchain" OR "block-chain" OR "block chain" OR "distributed ledger") AND TITLE-ABS-KEY ("food" OR "food supply" OR "food supply chain" OR "agriculture").
This collection is represented by a dataset, which includes works published in the English language. Since the word 'block chain' can refer to many areas, it was necessary to specify the subject areas, namely 'Business, Management and Accounting', 'Computer Science', 'Engineering', 'Decision Science', 'Social Science', 'Economics, Econometrics and Finance', 'Mathematics', 'Agricultural and Biological Science', 'Chemical Engineering' and 'Multidisciplinary'.

3.3 Studies selection and evaluation

The identified keywords were used as search terms in Scopus in early January 2020 to find relevant publications. Moreover, to have potentially relevant studies to be included in the analysis, different reference types, such as journal papers, conference papers, and review papers were included in the systematic review. The search with unique keywords led to obtaining 173 English publications from 2016 to 2020. The term of blockchain was invented with bitcoin by Satoshi Nakamoto in 2008, but no primary research papers were published before 2016 in the food supply chain. This may highlight the novelty of ideas in the field of the food supply chain by discovering the potential of blockchain technology and its implications for cybersecurity.

4. Bibliographic network analysis

The method used in this work is a bibliometric analysis, in particular, Systematic Literature Network Analysis, introduced by Colicchia and Strozzi (2012) and further developed by Strozzi *et al.*, (2017). It consists of two parts: the citation network analysis and author keywords co-occurrence network analysis. The SLR allowed for identifying a set of papers and helped to understand comprehension of main concepts and search strings. The 173 papers extracted from the SLR process were included to build and study bibliometric networks.

4 .1 Citation network analysis (CNA)

In the citation network, a network consisting of 173 nodes was constructed, composed of 125 isolated nodes and four connected components. The biggest connected component includes 42 papers and the other three include 2 papers each. Based on more structured information from the biggest component, only the connected components with 42 documents will be analysed. Questions are discussed by an overview of the citation network analysis. In the citation network, the connected publications depend on prior works that have influenced their research and present the flow of knowledge.

4.1.1 The biggest connected component

As shown in Figure1, the biggest connected component consisting of 42 nodes exists. It is possible to detect the existence of a main development trend of the field extracting the main path component (Lucio-Arias and Leydesdorff, 2008). The main path represents the "backbone of the research tradition" (Lucio-Arias and Leydesdorff 2008, Colicchia and Strozzi, 2012). As mentioned by Strozzi *et al.* (2017), "the Main Path highlights the articles that build on prior articles but continue to act as hubs in reference to later works". Indeed, in this work, the concentration was on the key-route main path, where key-route is the link that has the highest traversal weights (Liu and Lu, 2012). Its extraction was performed setting the rank numbers of key-routes from 1 to 10 and using Pajek, software for social network analysis (http://mrvar.fdv.uni-lj.si/pajek/), following the method proposed by Colicchia and Strozzi (2012).

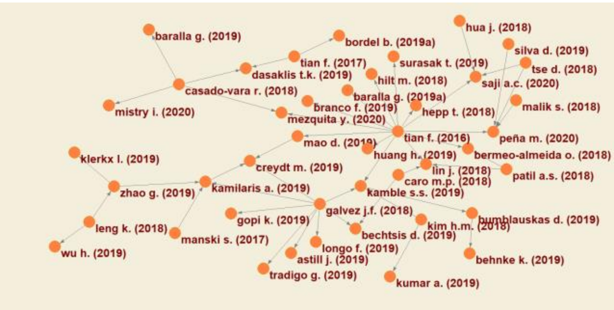

Figure1. Main connected components of the citation network

4.1.2 Main path analysis

Figure 2 depicts the main path of the biggest connected component, which includes 17 nodes. The nodes belong to three main streams: 10 nodes belong to the first stream, and 5 and 2 to the second and third streams, respectively.

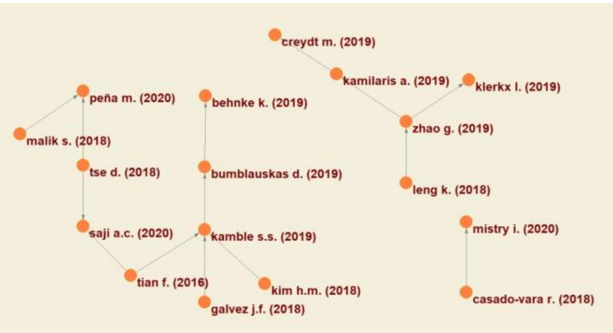

Figure2. The main path of the biggest connected component

4.1.2.1 Applying blockchain technology in the food supply chain traceability and authenticity

This stream of research focuses mainly on the use of blockchain for assuring traceability and authenticity in the food supply chain. The oldest paper, by Tian (2016), is a primary work with a high number of citations. He explored the use and development of RFID and blockchain technology in the Agri-food supply chain traceability system to improve food safety and quality based on the reliability and authenticity of the information shared by blockchain technology among supply chain participants.

Following Tian (2016), the emerging literature on the blockchain has begun to revolutionize different benefits and advantages of this technology which can have a direct effect on the supply chain that includes a range of features, such as overall processes transparency; improving trust issues in the transactions; traceable and tamper-resistant records; accessibility and visibility of data provenance; and a high level of traceability (Galvez *et al.*, 2018; Kim and Laskowski, 2018)

The paper by Kamble *et al.,* (2019) completed the literature focusing on blockchain adaption at the individual and organizational context. Associations between the most important blockchain technology enablers include traceability, auditability, immutability, and provenance, and the agriculture supply chain is tested by applying a combined Interpretive Structural Modelling (ISM) and Decision-Making Trial and Evaluation Laboratory (DEMATEL) methodology.

In the considered time window, studies appeared to concentrate on the investigation applications of blockchain technology from an organizational solution.

Behnke and Janssen (2019) suggested standardization of traceability processes and interfaces, joint platforms, and independent governance as the main boundary conditions before blockchain can be applied for sharing information to improve traceability in the dairy food supply chain. One start-up company (Bytable Inc) in the Midwestern USA tried to understand how blockchain technology and the internet of things (IoT) were implemented in the production and supply chain delivery system for eggs, from farm to consumer (Bumblauskas *et al.*, 2019).

The study conducted by Tse *et al.*, (2018), discussed various government policies in protecting information security and the use of blockchain technology as an innovative solution to record and transfer transactions with authenticity, safety, and security.

The blockchain solution based on a consortium framework is proposed by Malik *et al.*, (2018). They proposed "Scalable blockchain framework to support provenance in supply chains" and classified some security/privacy attacks, including (i) Double transfer; (ii) DOS/DDOS attack; (iii) Wallet theft; (iv) Sniffing attack; Sybil attack; (v) ID Spoofing; (vi) Spamming attack and some possible countermeasures (Malik *et al.*, 2018).

4.1.2.2 Maturity of blockchain technology in agriculture and food supply chains

In the second stream, the five papers range from 2018 to 2019. This stream is devoted to the maturity of blockchain technology in agriculture and food supply chains. The oldest paper, the one by Leng *et al.*, (2018), found that the current situation of the Chinese agriculture industry was ineffectively organized. Leng *et al.*, (2018) proposed an agricultural supply chain system with a double-chain structure; this system would be able to protect information privacy of the company and the security of transactions that can lead to the credibility of the public service platform and increase efficiency across the whole system. The paper used a systematic literature network analysis conducted by Zhao *et al.,* (2019) provided an overview of the state of the art by discovering the main applications of blockchain to improve agri-food value chain management, such as food safety, information security, and food traceability. In addition, some significant challenges were discovered in the adoption of blockchain in the agri-food value chain, including a lack of awareness and skills, policy and regulation barriers, and privacy issues.

The path then divided into two parts: one side includes two papers focusing on food safety and integrity through higher traceability (Creydt and Fischer, 2019; Kamilaris, *et al.*, 2019). The first companies to apply blockchain into their supply chain for tracing were Walmart and Kroger to track Chinese pork and Mexican mangos (Kamath, 2018). As a result of this project with blockchain, information about the origin of a bundle of fruits was accessible in just a few seconds in comparison with traditional methods (Wass, 2017). Another example of blockchain technology was launched by the European supermarket Carrefour to confirm standards and trace origins of food, such as meat, vegetables, and dairy products, from farm to fork (Carrefour, 2018). In this case, each product is equipped with a QR code which consumers use to see the details of the product.

The other side, instead, includes an article by Klerkx *et al.*, (2019), which examine different clusters of social science literature on digitalization in agricultural processes such as (i) Digital technologies adoption on farm; (ii) Effects of digitalization on the farmer's skills, knowledge, and identities; (iii) Data privacy, ownership, and ethical issues by digitalization of agricultural systems; (iv) Finance and agricultural supply chain management. A few studies reflect how smart farming systems are exposed to cyber-attacks. As reported by West (2018), the special security issues concerning the agriculture supply chain, such as ransomware, viruses and worms, SCADA systems vulnerability and malicious software, were addressed, and a risk-based framework with three components (abnormal measurement detection, access control, and encryption) was introduced to deal with the challenges of mobile computing and data-driven decision making in food protection. Another example is reported by Barreto and Amaral (2018), who affirm that major security risks and vulnerabilities arising from the development of new information systems and services are highlighted in the agricultural sector such as, sensitivity and privacy issues, ransomware, denial of service (DOS), cyber-espionage and social engineering includes hacking of people and human errors.

4.1.2.3 Industrial applications of blockchain

Another stream of research examines industrial applications of blockchain with the combination of smart contracts or IoT to improve the current logistic systems by increasing security, privacy, transparency, and mitigating transaction times. Casado-Vara *et al.*, (2018) proposed a new simulation model of the supply chain via blockchain and multi-agent systems for providing the security of transactions in the food supply chain. In another study by Mistry *et al.*, (2020) presented a systematic literature review of blockchain-based 5G-enabled IoT for tracing various transactions and databases that can prove authenticity, consistency, security, and privacy in future Industrial automation such as smart home, smart city, healthcare, agriculture and autonomous vehicles.

4.2 Author keywords analysis

The author's keywords analysis will be useful in detecting patterns in research that cover the knowledge in all papers (Ding, *et al.,* 2001). Questions are addressed through co-occurrence network analysis. The network map (Figure 3) is the results of the VoSviewer software that performed this method. A discussion about a whole set of works contained in the author's keywords network has been presented in the following.

4.2.1 Emerging technologies applications in sustainable and transparent food supply chain (Blockchain technology; Food supply chain; Sustainability; Transparency)

The biggest cluster is referred to enhance the use of emerging technologies such as Internet of things (IoT), blockchain, and big data as potential enablers of a "data-driven sustainable agriculture supply chain" (Kamble *et al.*, 2019) and improve transparency. Blockchain technology facilitates safely information sharing across the whole supply chain. The information stored on the blockchain platforms can be accessed and it is not possible to manipulate by anyone and from the customer perspective, they can monitor food information from their smartphones more accurately, which reinforces their confidence. According to Yiannas (2018), trust, security, and transparency in Wal-Mart's food supply chain obtained by blockchain technology adaption through digitizing documents and registering data from parties who access to blockchain. Subsequently, human errors can be controlled, the chance of corruption and risk of food fraud can be significantly minimized.

4.2.2 Different architectures based on blockchain and smart contracts (Blockchain; Distributed ledger; Smart contracts)

Traditional supply chain systems typically have a broad range of problems including lack of communication, long delays for obtaining information, and unreliability in product monitoring (Wu *et al.*, 2017). To address the aforementioned problems, this cluster is devoted to a presentation of different supply chain architectures based on distributed ledger technologies using blockchain and smart contracts. The complexity of a supply chain can be minimized, and the operations can be controlled by using smart contracts. Baralla *et al.*, (2019) proposed a traceability system with a Hyperledger Sawtooth platform in an agri-food supply chain that can be integrated with current technologies for dealing with the issues arising from current technologies related to the centralization of information. The principle purpose of the application is to eliminate centralization by increasing trust between supply chain members, enabling the integrity of data by the authorized members and the customer requests are replied with transparency and irreversibility. Another study by Shyamala Devi *et al.*, (2019) designed an architecture by a combination of IoT and blockchain for smart agriculture which increases the performance of security and transparency of data.

4.2.3 Traceability database systems to ensure food safety (Blockchain; Food safety; Supply chain; Traceability)

The origin (tracing) system of agricultural products is essential for the safety of foods, however, due to multiple and distributed stakeholders, it is difficult to manage data with a centralized approach. Consequently, it is difficult to have a transparent and trust production procedure. Therefore, researchers propose different agricultural traceability systems based on techniques of blockchain with inherent features which include decentralization, openness, security, and privacy. In the paper by Bettín-Díaz *et al.,* (2018), presented a new methodology of integrating the blockchain technology to track and trace the provenance of the organic coffee and provided the consumer with sufficient details on the origin of the commodity for deciding on the purchase. The conceptual framework by Marinello *et al.*, (2017) addressed also the possibility of building an "animal product supply-chain traceability system" based on blockchain technology, increasing the safety and quality of food, and a significant reduction in food loss during transportation.

4.2.4 Security and Privacy challenges in IoT systems (Ethereum; IoT; Security; Smart contract)

Smart applications of Internet of things (IoT) extend from Industrial control systems in smart agriculture, supply chain management, smart transportation, to smart cities. However, collected and processed data by IoT systems are vulnerable to accessibility, integrity, and privacy threats. Makhdoom *et al.,* (2020) presented a "Privacy Sharing" on an innovative blockchain system for the protection of data into different types of participants, including energy suppliers, banks, insurance companies, and other actors. Data within a channel is encrypted and managed by embedding access control systems in a distributed way. Mohanta *et al.,* (2019) applied the decentralized blockchain technology with an Ethereum platform in IoT systems to deal with security and privacy challenges in the healthcare insurance sector. The results are proved by showing trust management, security, and privacy data.

4.2.5 Combination of IoT, Edge computing and Blockchain (Edge computing; Food traceability; Internet of things)

The term 'Edge computing' refers to a distributed computing paradigm that makes a wide range of applications from large scale sensor networks to IoT and brings many advantages for example scalability, improve response time and save bandwidth. Tošić *et al.*, (2019) conducted a survey that relied on a decentralized approach with a combination of blockchain and a consensus algorithm into an application container platform for monitoring network resources. Alonso *et al.,* (2020) performed a platform relied on the application of IoT, Edge computing, and blockchain techniques to monitor livestock and crops and resource management in a dairy farm.

4.2.6 Blockchain as a solution in the agriculture supply chain (Agriculture; Food security; Supply chain management)

Current trends in the supply chain are faced with some challenges include lack of transparency and trust, frauds, security errors in IT systems, integrity in digital records. Demand for transparency and information from customers is increasing over time, but current systems cannot provide such data. To solve the aforementioned problems, different mechanisms for blockchain such as smart contracts, decentralized platforms guarantee the security and tamper-resistance (Ge *et al.*, 2017). In the study by Basnayake and Rajapakse (2019), mechanism of blockchain-based Ethereum smart contracts was used in the agriculture supply chain for creating transparency and trustworthiness of transactions among users, quick response (QR) code has been applied as a solution for identifying any food product from farm to fork.

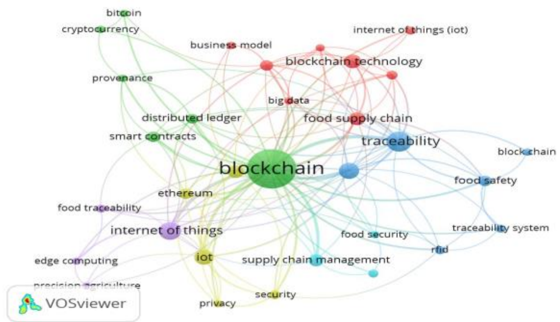

Figure 3. Authors keywords' co-occurrence network

5. Conclusions; research gaps and future research directions

In this study, we conducted an SLNA to depict an overview of the existing literature to study the evolution of cyber-risks, cybersecurity solutions, and blockchain solutions. Below, we summarized the research gaps and future research directions on blockchain technology that various researchers proposed in managing cyber risks in the food supply chain based on a systematic review of the literature.

In the context of capabilities and strategies of the supply chain to apply blockchain as a key component of cyber supply chain risk management in the food supply chain; as emerges from our analyses, on one side works have concentrated on applying blockchain technology in the food supply chain traceability and authenticity, fight fraud and minimize the system errors and its maturity into emerging technologies for cybersecurity solutions. On the other side, some contributions proposed different blockchain systems, models, and architectures alone or in combination with other technologies to manage privacy and security challenges, sustainability and transparency in the food supply chain, blockchain's role as a solution for privacy and security challenges, and traceability database systems to ensure food safety and security. Most of the proposed blockchain systems traceability database systems are staying in the academic stage and there are a few practical types of research in reality. This scenario is affirmed by the third stream in Mainpath analysis demonstrating how just a few industrial applications of blockchain are reported in the literature. To address this gap, more efforts are required to study some special case-studies for implementing blockchain and smart technologies in some companies within the food industries, such studies will be crucial to develop a framework by recognizing stakeholders, steps, processes, technical requirements and level of coordination, as well as the rules for effectively securing food supply chain context. This could also be extended to standardizations, compliance, and forensics, with particular reference to the impact of the role of third-party regulators and authority organizations to shed light on how the blockchain technology can be implemented in the industrial community.

In terms of implications, this study contributes an outlook of the most established study areas on the cyber-risks, cybersecurity solutions, and blockchain paradigms, that is how these are changing and evolving over time thereby assisting newcomers to aim and adopt any of the identified themes as their research focus. Lastly and holistically, this study contains also an additional contribution by the application of the SLNA methodology based on the bibliographic patterns that can be of benefit for discovering agendas and themes for further research in the realm of blockchain and cybersecurity solutions.

6. Disclosure statement

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