Blockchain Applications in Agriculture

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Blockchain is a distributed, immutable ledger technology initially developed to secure cryptocurrency transactions. Following its revolutionary use in cryptocurrencies, blockchain solutions are now being proposed to address various problems in different domains, and it is currently one of the most "disruptive" technologies.

Keywords: blockchain ; distributed ledger technology ; agriculture

1. Introduction

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

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

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

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

1.1. Blockchain Technology

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

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

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

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

1.2. Blockchain Technology in Agriculture

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

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

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

- Product traceability and logging (e.g., IBM Food Trust [32], Ambrosus (https://ambrosus.io, accessed on 15 June 2022), and TE-FOOD (https://te-food.com, accessed on 15 June 2022)): Consumers and regulators can ensure the origin of the products. Moreover, they can store product information from IoT devices and sensors.
- Ensuring trust between participants (e.g., TrustChain [28]): Blockchain can help supply chain participants trust each other through the transparency and immutability it can offer.
- Providing equal pay to producers (e.g., FairChain (https://fairchain.org, accessed on 15 June 2022)): Blockchain can be used to reduce intermediaries and distribute profits transparently to producers.
- Product insurance and claiming compensation (e.g., Etherisc (https://etherisc.com, accessed on 15 June 2022)): Smart contracts can replace insurance documents and schedule insurance activation according to IoT sensors. All the transactions are transparent and visible to other parties.

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

2. Blockchain Frameworks

One of the primary findings was the variations in the specific blockchain framework used. The result reflects the situation that prevails in the overall ecosystem of the blockchain. Most solutions use Ethereum and Hyperledger Fabric. Beyond that, a large percentage do not mention the blockchain technology they use. The papers that do not mention technology are mainly conceptual (67%, 22 out of 33 papers). Apart from the above in the use of blockchain in the agricultural sector, other technologies have been used less frequently, such as Hyperledger Sawtooth (3%), IOTA (1%), NEO (1%), Corda (1%), and Multichain (1%). Two assistive blockchain-based technologies, BigchainDB (4%) and Polkadot (1%), also appear. Finally, seven research papers in this field combine more than one technology. All these papers use Ethereum combined with another technology [37][38][39][40][41][42], except one [43]. In one of them [42], Polkadot is used for two-chain communication, which allows cross-blockchain transfers.

3. Data On-Chain and Off-Chain

Blockchain technologies show the ability to handle various security issues. An important aspect in this direction was the identification of data stored on-chain and off-chain. Blockchain technology has been proposed more frequently for storing data by sensors and IoT devices in order to monitor specific aspects of the production process. This appears in 43 research papers (41%). These data are mainly used to monitor the process and, secondarily, used to manage information or the product. In addition to the above, there are four solutions that store access control and authentication policies, for IoT devices, on-chain [44][45][46] but also off-chain [47]. Some research papers suggest the periodical storage of data in the blockchain [39][48][49][50][51][52], so as not to unnecessarily burden the additional cost of storing and using the blockchain. In some cases, an external database is usually used to store the aggregate data [49][50][52]. In the corresponding category of solutions, there are also approaches that store only anomalies presented in the data from the IoT devices [49][50][53][54][55]. This is usually to ensure the integrity of the information and not to distort it. Almost all of these solutions that store only critical data in the blockchain have external storage. Both in the case of periodic storage and in the case of abnormal storage, all solutions use Ethereum, except one that uses Hyperledger Fabric. This makes sense because, in Ethereum, storage costs are taken into account when creating the architecture.

Another common architectural scheme in creating decentralized applications is to store hashes in the blockchain and actual data in external storage. Most architectures use IPFS to store agriculture data and the blockchain stores either the IPFS hash [56][57][58][59][60][61][62][63] or the data hash [42][43][64]. There is a study [42] that stores data from sensors in IPFS, then the hash of this data is stored in a private permissioned blockchain, while the block hash of this blockchain and the height of the block are stored in Ethereum. In the latter, an incentive mechanism is activated, through a smart contract, to reward the user who performed the mining in the private permissioned blockchain. In this way, the authors achieve the security that a private permissioned blockchain would not have.

As reflected in the research, a new trend in the blockchain is the digital representation of real-life assets through a digital twin. A digital twin is a virtual representation of a physical object or system, usually in multiple stages of its life cycle [65]. As Pylianidis et al. [66] point out, the use of digital twins could bring significant benefits to the agricultural process. The blockchain has also been proposed to represent digital twins using tokens. The research that has been conducted represents products as tokens (following the ERC20 token standard) that are indirectly related to the agricultural sector, such as water and energy that farmers need to share [38][67]. Their use as a currency for transactions between producers and buyers has also been suggested [68]. They can also be used as a reward system for the virtuous use of water [69], where the smart contract is a digital twin of an IoT device that monitors water consumption. Due to the lack of infrastructure, the researchers created a module for IoT devices to communicate directly with the smart contract [69][70]. According to the findings, no research has been conducted on the digital representation of the product, which would help in the certification and traceability of the product from the farm to the fork [71].

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

4. Solutions Maturity

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

The evaluation of the proposed solutions is achieved using datasets from companies and IoT devices [64][72][73], data created artificially [41][74], and real-world data from the agricultural sector [43][54]. There are also applications in the findings where evaluation is limited to laboratory tests or simulations. Based on the results, the researchers only found three prototype applications [75][76][77]. All these prototype applications were published from 2020 onward, showing us that maturity is now growing, and real applications are being created. In addition, the researchers identified four solutions in a pilot phase that have been installed, tested, and used in real conditions. The first application [78] is a pilot, mainly in Nigeria, with the aim of renting tractors for agricultural work. In the works proposed by Wang et al. [63] and Yang et al. [79], the main focus was on the traceability of products, and they have been applied in factories in China. These three applications have been created using Hyperledger Fabric. Finally, another research work [80] uses the IOTA Tangle network to record the data from IoT devices and is in a pilot application in three farms in Greece. Interestingly, no application that uses Ethereum as blockchain technology is yet at this maturity level.

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

5. Variety of Agricultural Products and Countries

The use of blockchain does not focus primarily on a specific product. Instead, there are general terms, such as crops, organic food, and water, that are mentioned in most studies, but beyond that, there is a dispersion of 31 different products. It is interesting to notice that the researchers have more references to farming products than to animal products. Although the difference is about three times smaller, 39%, e.g., [62][81][82] vs. 14%, e.g., [57][76], a significant percentage (38%) of the solutions do not indicate the industry to be used. A small percentage (9%) refers to goods needed in the agricultural sector, such as water, energy, and proper waste management. This shows us that researchers can focus on specific products that would be in line with blockchain logic but also that there is a need for agnostic solutions in the supply chain.

The systems created for specific countries try to solve problems in the essential products of each country, but no specific association of an individual product with each country is shown. Even in China, for which more solutions have been created, mainly agricultural products are mentioned. Finally, it is worth noting that most current solutions are proposed for Asian countries.

6. Reason for Using Blockchain

Here, the reason for using blockchain in the agriculture sector is also researched. These reasons are mainly to solve the various cyber threats and food safety issues of the existing IT solutions in agriculture. As a result, most solutions use blockchain for its inherent characteristics, such as data transparency and integrity. This happens at 61% and 50%, respectively. Moreover, few papers (3%) [41][56][83] use another intrinsic feature of blockchain technology: its data availability. It should be mentioned that many solutions involve the use of blockchain over conventional databases due to the availability provided but do not clearly define it, so it has not been included in the respective count. In addition to the above reasons for using blockchain, a typical process is storing product information and tracking information. This immutable data logging is used in most research papers (72%), e.g., [79][84][85]. It should be noticed that although blockchain is used for logging and storing data, such as IoT data (solving the problem of counterfeiting), it should not be misused. Blockchain in general and especially public permissionless blockchains should not be used to store the overall data of an application. Such storage is costly and increases the size of the blockchain, making it non-functional. Instead, blockchain technology should be used as designed to store critical data to which the blockchain gives an immutable feature. Another common reason for using blockchain is traceability, which is found in 18% of the solutions, e.g., [41][86]. As before, we need to be aware that some solutions misinterpret that traceability is an inherent feature of blockchain, which is not entirely accurate. Although the ledger itself provides traceability, this possibility cannot be easily and efficiently achieved without a specific architecture and without third-party frameworks [34].

Blockchain has also been used to schedule various processes in the agricultural sector. Scheduling may involve hiring machinery from farmers for specific tasks [78][87] or hiring seasonal workers for agricultural jobs [88]. It may also involve priority scheduling for defined tasks with robot coalitions [83] or fixing IoT devices using autonomous drones [51]. Based on the findings, blockchain technology has also been used to provide access control solutions [44][45][77][89][90][91][92]. These solutions store data in the blockchain for access control, such as the public keys and access policy, for security reasons. Most devices for which access control is used are IoT devices. Finally, the blockchain has been utilized as an incentive mechanism for the effective management of waste by farmers [93].

7. Provided Service Area

Following the research question about the reasons for using blockchain, the researchers examine which service is provided by the respective applications. Based on the findings, more than half of the applications have been created to provide product monitoring or management. This is observed in 55% and 75% of the papers, respectively. A unique feature is that most applications (61%), which have been created for product monitoring, store data from IoT devices, e.g., [50][89]. In the case of management, this may relate to the process by which the product went through the various stages of production as well as its resale, e.g., [41][94]. This model of all transaction availability promotes the circular economy model. Most of the time, management and monitoring are combined in the proposed solutions. Management can also refer to the coordination of processes, such as the rental of equipment [78], the use of robots [83], and the proper distribution of a good such as water, energy, or waste, e.g., [67][70][93].

Although not so many applications have been created extensively, one industry that developed mainly after 2019 is product certification (8%). In most cases, the provided solutions certify the authenticity of the product's origin [86][95] and the conditions under which it was developed [53][82]. Therefore, the data stored in the blockchain are related to both the product and the process other than the IoT data. It is noticed that they refer more often to organic products and are mainly interested in the transparency and integrity provided by the blockchain. Furthermore, a research paper uses GIS to prove the location [95].

A different emerging field of blockchain applications in agriculture is auctions (3%) and product trading (4%). In the first category, the researchers identified three research papers [73][81][96] that proposed a system of offers for the sale of agricultural products. All these proposed solutions belong to the farming sector. Respectively, there are applications that deal with the trading of either agricultural products [97] or energy and water for crops [38][67]. In addition, there is a proposed solution that exchanges products based on the farmer's rating [98].

Other services provided by agricultural blockchain applications are reputation (4%) and reward systems (3%). The rationale for a reputation system is clear, and such systems aim to capture product and producer ratings. The reason for using blockchain in such applications is the integrity that it provides, something that the research thoroughly verifies [61][62][98][99]. Additionally, blockchain is highly associated with reward system applications. More precisely, the researchers observed that all incentive solutions related to data management are also indirectly related to blockchain, such as water [69][70] and waste [93]. The validation of the incentive mechanism is performed by the IoT data stored in the blockchain. Finally, one last type of provided service is data sharing, and blockchain is used for authentication [90] or as an incentive mechanism as mentioned above [40].

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