THE ROLE AND POTENTIAL OF BLOCKCHAIN TECHNOLOGY FOR THE FOOD PROCESSING INDUSTRY: A SCOPING REVIEW

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Abstract

Through its multiple applications such as traceability and optimization of the food supply chain, achieving food safety and reducing food waste or implementing smart contracts, blockchain technology is proving its usefulness in the food processing and distribution industry. Stimulated by the current advances and the high interest in this relatively recently emerged topic, characterized by a limited number of implementations in the food industry, the paper aims to conduct a bibliometric scoping review. This type of analysis provides an overview of the aspects, applications and technical details of the implementation of this technology in the food sector. A survey of the relevant literature, still in its infancy, reveals recent solutions and implementations that have the potential to exert a major influence on developments in the field. In contrast to existing review-type analyses, this paper incorporates the key aspects of blockchain technology implementation related to food processing, distribution, traceability and pricing.

The paper summarizes the benefits but also the challenges related to the adoption of blockchain technology in agri-food, providing a comprehensive perspective on the state of the art and its essential role in ensuring sustainable agricultural production, reducing food waste, improving food security and integrating into a circular and resilient economic framework. Therefore, blockchain-based technologies reveal themselves as important tools for implementing the EU's "Farm to Fork" strategy.

Keywords: blockchain, agri-food supply chain, scoping review, Platform Ethereum, smart contracts, Agriculture 5.0

JEL Classification: Q1, O13, O32, G38

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Introduction

The advent of digitalization, known as the fourth industrial evolution of Industry 4.0 is synonymous with the emergence of several new technologies. Technologies like, artificial intelligence, internet of things (IOT), sensor technology, 3-D printing, revolutionising the way known tasks are carried out, thus generating and empowering to new business practices, tools and technologies (Öztemel and Gursev, 2018; Zhou and Le Cardinal, 2019). Due to their novel capabilities, and results that greatly surpass the existing technologies and processes, there is a major drive to take advantage of them through diffusion in a variety of fields: manufacturing, medicine, etc. (Schwab, 2017).

Smart agriculture and digital transformation in food production and consumption are already being put into practice (Hassoun, et al., 2024). Drone technology and sensors are increasingly used (Hassoun, et al., 2024) amid a stagnant or declining labor force.

The quality and reliability of food processing and distributions have always been a major source of concern for both rich and poor nations. While the focus and issues may differ, ranging from insufficient food supply and food shortages among some of the poorest nations, to the need to ensure a quality supply of food which will not endanger public health and enable citizens of developed countries to lead healthy, productive lives, the need to ensure traceability of food-related agricultural products throughout the dedicated production and supply chains is one of the top concerns (FAO, 2024). These, and sustainability objectives aimed at reducing the impact of agriculture and food production on the environment through improving the efficiency and reducing waste in the food production and supply chain, and combating food fraud are key tenets of European Union's Farm to Fork strategy (EC, 2020).

There are other aspects, over-production, harvesting and breeding practices have set concerns about the quality of the food that is being produced and consumed, Fair practices and traceability to address them, also with respect to fair trade practices (FAO, 2024).

New technologies have showed promise in terms of achieving a higher quality of food and a more efficient supply chain. Sensor technology and IOT have made food production and distribution better, by ensuring that optimal production, storage and distribution conditions are achieved, things that are critical in situations defined by food shortages, production and transportation bottlenecks (Tang, et al., 2024). These advancements are likely to improve the overall performance of the food production and delivery, and help increase food security, especially in places in which this is a major concern (Tang, et al., 2024).

However, these technologies are not the only ones which can improve the quality and efficiency of the food chain. Blockchain technology has received a lot of attention lately in terms of traceability of the origin and movement of food „from farm to fork" (Vu, et al., 2023). Aside from the aspects concerning traceability at virtually every step of the production process, the technology has proven itself useful in particular for small operators (farmers, producers, distributors) not only to ascertain the quality of their products, but also to engage in smart contracts, which allows automatic matching between business-to-business (B2B) buyers and sellers, with sizeable positive impact in matching supply and demand, and therefore reducing food waste, addressing supply disruptions and ensuring more equitable prices for both producers and consumers (Land and Siraj, 2021).

Considering these aspects, the main contribution of the paper is to provide a comprehensive overview on the importance, relevance and specific challenges of implementing blockchain technology in agriculture (BTA) and food processing, taking into account the novelty of the field that has emerged and developed over the last 10 years, as well as the few implementations known at present.

In view of the novelty, the early stage of knowledge, the limitations imposed by the few specialized implementations, the research question is to identify the most relevant issues emerging in the literature on BTA, revealed by the present bibliometric summary analysis. The practical aspects of implementation are also pursued, usually addressed in articles focusing mainly on technical aspects, omitting the rigorous treatment of aspects specific to the agri-food industry.

The research is structured in five sections. The introductory section is followed by the section explaining the elements of the blockchain methodology essential to understanding the implementations discussed in the analysis section. The third section details the specific methodology used for review articles, consisting of making a relevant selection of academic papers based on objective criteria. The fourth section uses co-appearance analysis to identify the main implementations and features of BTA based on the content of the selected relevant papers. The concluding section summarizes the main elements revealed by our analysis, discusses their relevance in the context of the current state of knowledge and existing concrete implementation.

1. Blockchain technology and key relevant features

Blockchain technology forefront of the new technologies mainly due to the advent of cryptocurrencies. Their main innovation consists in the existence of a decentralized ledger of transactions, grouped in blocks (figure no. 1), which contain both current transaction data, and hashes and data coming from previous transactions (Giganti, et al., 2024). Thus, a chain of transactions which contain and validate transactions several times is formed, with the information stored in several mining notes, with the property of being immutable by design (Metcalfe, 2020).

The Blockchain technology has emerged at the forefront of new technologies mainly due to the emergence of cryptocurrencies. The main innovation lies in the existence of a decentralized ledger of transactions, grouped into blocks, which contain both current transaction data and hash functions, respectively data from previous transactions (Giganti, et al., 2024). Thus, a chain of transactions is formed (Figure 1), validated several times, the information being stored in several transaction processing nodes hosted on computers or servers, with the property of being immutable, which implies that it can never be modified or deleted during the existence of the blockchain structure (Metcalfe, 2020).

The Ethereum network appears very often in the BTA literature as it allows deployment and execution of smart contracts. Smart contracts are computer programmes that can be run on the Ethereum network, and execute when specific conditions are met (Metcalfe, 2020). These allow seamless execution of transactions, e.g... to certify agricultural goods (Giganti, et al., 2024), automatic payments to suppliers once delivery and confirmation of the product conditions are available (Vu, et al., 2023), and are stored in the blockchain the same immutable way as transactions do (Metcalfe, 2020).

Adoption of BTA depend, among other factors on its ability to be user-friendly and allow a wide range of participants to access information and engage in transactions (Tang, et al., 2024). For them, writing and implementing a smart contract is often out of reach as it requires specific knowledge. Therefore, there is a need for frontend user interfaces that allow participants to monitor and engage in transactions (Kechagias, et al., 2023).

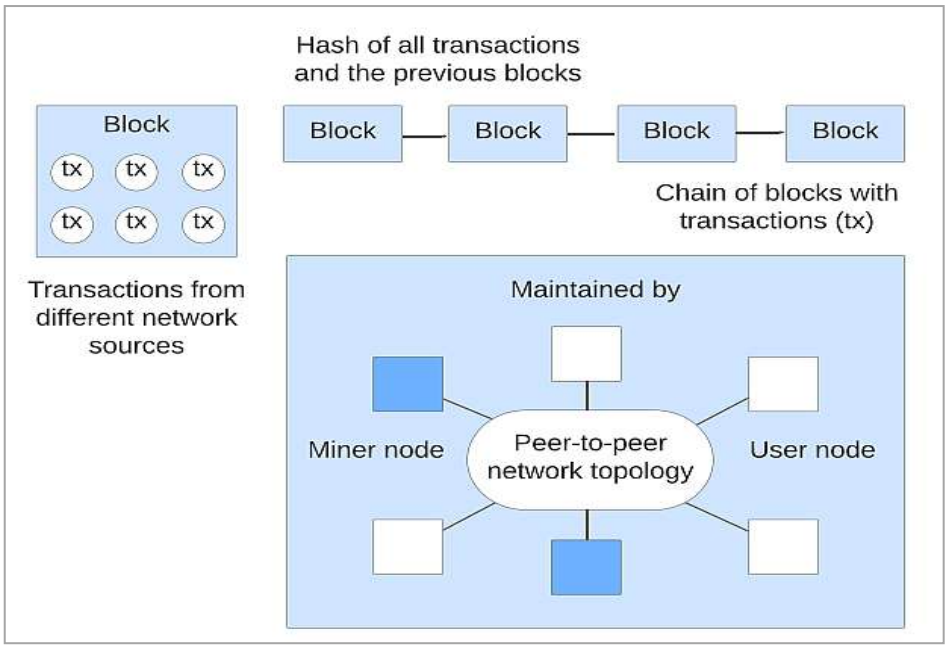

Figure no 1. Structure of the blockchain
Source: Giganti et al., (2024)

As a technological enabler for agriculture, blockchain implementations often go hand in hand with IOT technology. Thus, data from sensors, integrated in smart devices, can provide real-time data on food products at different stages at the supply chain, fed into the blockchain (Tang, et al., 2024) and complement transaction data with information about storage conditions, location, quality, crop management, to name a few (Rehman, et al., 2023). This information can also be used as input for smart contracts, enhancing thier applicability and usability (Peng, et al., 2023).

2. Methodology

The research approach chosen is scoping review. This option, similar to other review types has a systematic character due to the use of a methodology based on specific criteria (Page, et al., 2021). Scoping reviews emphasize the examination of complex issues, for which the literature is relatively unstructured, thus being the most appropriate option for the purpose of achieving an overview of the BTA field as a starting point for identifying areas/niches with genuine research potential, suitable for further systematic approaches (Gottlieb, et al., 2020). Also, in order to achieve an exhaustive overview of BTA, it was deemed necessary to complement existing review approaches focused on more specialized topics having a much narrower scope.

The paper adheres to the PRISMA 2020 criteria for systematic literature reviews (Page, et al, 2021). The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) methodology consist of a checklist of items needed to identify a systematic review, starting from the title and abstract to the presentation of search and selection strategies, methods to analyse data and synthesize results, along with characteristics and risk biases considered in the research. However, the authors of the paper have determined that certain elements cannot be considered relevant. The reasons for this were the fact that PRISMA focuses on health care/life sciences research, and the perception that the novelty of the topic (predominantly review-type articles based on current information on blockchain technology implementations in agriculture published after 2022) would not provide a sufficient basis for an overly restrictive approach with regard to the existence of possible gaps and biases in the literature. Also, the limitations imposed by the editorial policy weighted in favour of including factual information and significant findings instead of some of the items which will enhance compliance with the PRISMA 2020 criteria. The Scopus database, used in almost all the review articles selected for in-depth analysis (e.g. Giganti, et al., 2024, Thirukumaran, et al., 2024, Chiaraluce, et al., 2024), was chosen for getting bibliometric data.

An initial investigation using the terms "blockchain" AND ("food" OR "agriculture"), as well as similar combinations using variants of them (e.g. block-chain, agri, "agri-food"), conducted on November 17, 2024, revealed a large number of articles, over 40,000. The frequency of items by year of publication revealed that the relevant literature is almost exclusively concentrated in the 2016-2024 period. The analysis of a sample of papers revealed that the terms "blockchain", "agri food", "food industry", or similar words were just mentioned, without any detailed analysis being carried out or discussed. Therefore, we introduced criteria to select papers that actually analyse and discuss implementations of blockchain technologies in the food industry, similar to Chiaraluce, et al. (2024) while retaining the conditions that include the original keywords. In order to ensure a final relevant selection, only papers whose abstracts include items that specifically refer to blockchain technologies in the agri-food context were chosen. Figure 2 also details the other selection criteria used by the authors and the results obtained.

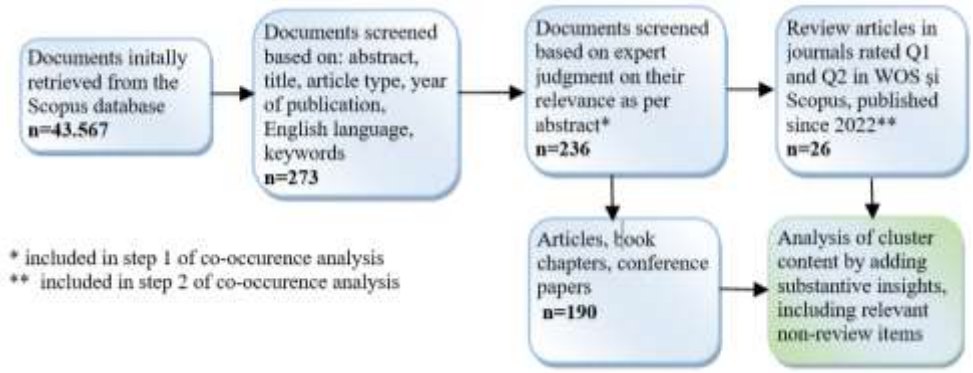

Figure no. 2. Document selection and review flow

For the bibliometric analysis we used the software package VosViewer, version 1.6.20, as employed in most of the review articles selected for this analysis. Bibliometric analysis is

carried out through mapping co-occurrences between keywords (represented as nodes) based on their strength, counted through appearances and links between them. The options used were: 1) keywords/terms as the unit of analysis, highlighted as nodes 2) full counting, useful in identifying the frequency of occurrence of terms 3) retention of terms with at least 10 occurrences 4) elimination of terms considered irrelevant (e.g. "article", "research") 5) use of network visualizations, where the frequency of co-occurrences determines the size of the nodes, and the number of links reflects the influence of a term on the other keywords 6) formation of clusters containing a minimum of 7 terms 7) obtaining balanced cluster structures for which the ratio of the number of terms between the largest and smallest cluster is a maximum of 2 to 1 8) using the strength of association between terms as a normalization method 9)using the frequency of occurrence as weighting method to determine the size of nodes/terms.

The bibliometric analysis was performed in two stages: 1) co-occurrence analysis for 236 papers based on titles, abstracts and keywords, and 2) co-occurrence analysis using the corpuses build from the methodology, results and conclusions sections of 26 review articles from journals ranked Q1 or Q2 in WOS. Thir approach was chosen following the evaluation of the results obtained in Phase 1, whose high degree of generality did not allow for a comprehensive overview of the state of knowledge, specific applications and problems related to the implementation of BTA.

3. Analysis and discussion

The first step of the co-occurrence analysis was carried out on the Scopus citation information (title, abstract, keywords) available for the 236 papers. Using the thesaurus feature, we have applied common labels for similar items e.g. agri-food, food industry, and eliminated items that were irrelevant e.g. article, review, researcher. To improve the relevance of visualizations, the words "agribusiness" and "blockchain" were omitted as they appear in almost all documents, thus distorting by frequency other important co-occurrences relevant to the BTA domain. The resulting cluster structure has four clusters, with 676 links, for a total link strength of 2615, grouping a total of 41 items. The results in figure 3 provide a basic overview of the main features of the blockchain literature devoted to the BTA literature.

The red cluster (13 keywords) gives an overview of BTA links with other themes at a broad, conceptual level. Thus, apart from being related to salient general issues such as *sustainability of the agriculture food supply chain* (AFSC), food security, food waste, BTA is often discussed in conjunction to other innovative technologies such as internet of things (IOT), big data and artificial intelligence.

The green cluster (13 keywords) which is the other most important cluster, reveals the perceived features and benefits of BTA. Thus accountability, food origin, and fraud identification appear to be directly related to the food-related products, markets and consumer concerns. In turn, the effectiveness of this technology is also closely tied to two main features of BTA, namely smart contracts and immutability of (recorded) transactions, as key features of a blockchain ledger (term not visible in figure 3, but belonging to this cluster).

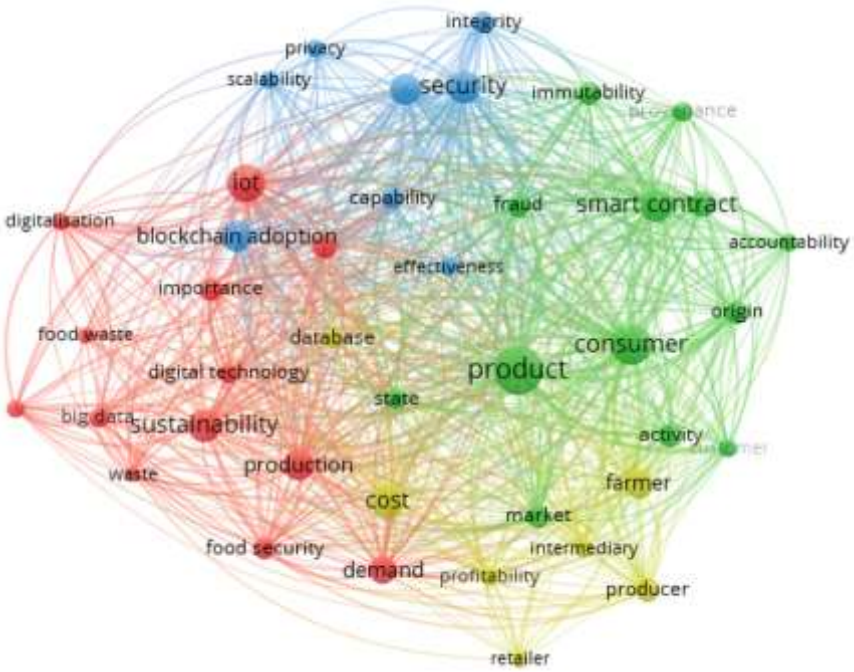

Figure no. 3. VOSviewer co-occurrence analysis on citation information

The blue cluster (8 keywords) groups features relevant to actual BTA adoption, integrity, scalability, privacy and security, as key features for an effective blockchain network.

The yellow cluster (7 keywords) somewhat less important in terms of the information provided, highlights the main elements related to the role of BTA in food distribution networks, relevant for most of the actors involved in the AFSC: farmers, producers, intermediaries and traders: costs, database operationalization and profitability.

Although the results provided a comprehensive overview of the BTA domain, highlighting links with other knowledge domains, perceived benefits, related technologies and characteristics related to its adoption, it was considered, after inspecting the topics of the papers and keywords, that many relevant items were not captured by this cluster structure: implementations recognized for their viability and operability, as well as specific technological challenges, which, if missed, could lead to a distorted, partial picture of the field.

Therefore, it was found necessary to deepen the analysis and conclusions reached in step 1. Thus, the methodology chosen for step 2 sought to achieve the main research objective, that is, to obtain an overview of BTA as exhaustive as possible. For this purpose, the entire content of 26 review articles was used, which, unlike other fields, represent a major source of information due to the novelty of this industry and the lack of formal references in the academic literature. (Zarbà, et al., 2024). Our choice was also guided by the heterogeneity of the other 190 items, guided by the heterogeneity of the 190 research articles, which, by pursuing particular aspects of the BTA theme, may lead to biases inherent in partial

coverage of a theme at an early stage. In comparison, review articles are distinguished by a better coverage of the BTA theme, are more suitable for building an exhaustive overview (the aim of this article), as they are better suited to the design of a cluster structure that, in a first phase, selects keywords with a minimum number of occurrences (10 in our case).

An inspection of the 40 available reviews included in the final selection of papers (see figure no. 2) revealed the fact that most of them have been published since 2022. Moreover, papers older that that date were focusing on the potential benefits of BTA in the context of Industry 4.0, and less on practical aspects such as successful use cases (e.g. wine industry) or implementation solutions (e.g. Ethereum network).
Thus, we chose to perform a content-focused bibliometric analysis of 26 review papers, published since 2022 in prestigious journals rated Q1 or Q2 in Clarivate/Web of Science or Scopus databases, e.g. Journal of Cleaner Production, Food Control, Computers and Electronics in Agriculture, British Food Journal, Agriculture. We have built a corpus of their content by selecting only the body of the papers which contained relevant information: in-depth description of the BTA field, analysis results, conclusions and discussion sections. Consequently, we have expanded the thesaurus to exclude items that were not relevant to the topic (e.g. research methodology details) and merged words that we found, after a preliminary analysis, referred to relevant items (e.g. things referred in most cases to IOT).

The results of the second step of the co-occurrence analysis, presented in figure 4, was used to guide us in synthesizing the most important features of the BTA literature. The authors' objective was not to focus on a review of a particular aspect of the adoption of blockchain technology applications (BTA), e.g. the wine industry, or the blockchain technologies used for implementation, but to give a broad (scoping) overview of the BTA knowledge as a starting point for any research connected to it in a meaningful way.

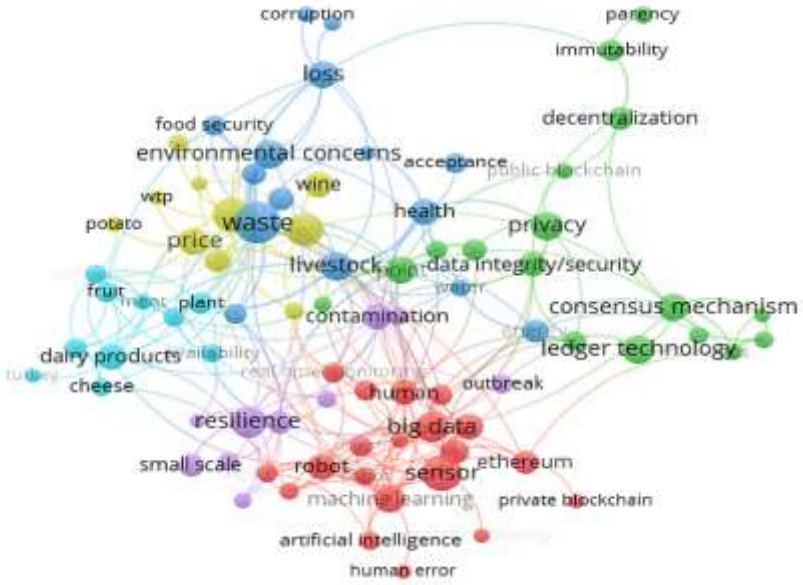

Figure no. 4. VOSviewer co-occurrence analysis on relevant corpus information

The second co-occurence cluster structure is characterized by 6 clusters, 247 links between elements/nodes, 82 nodes, for a total link strength of 433 (lower than the first cluster structure, appropriately reflecting the increased heterogeneity of the synthesized information).

The red cluster (20 keywords) groups most of the technology items that associate with BTA as part of Agriculture 5.0 (Hassoun, et al., 2024). Thus, BTA adoption is cited along with the use of artificial intelligence, big data, machine learning, use of radio frequency identification (RFID) tags, sensors, cloud technology, use of robots and cobots, drones, edge computing and digital twins. These technologies are aimed at identifying products, establishing/enforcing property and real-time monitoring of the food supply chain. Ethereum network is identified as the main technology enabler of BTA, and energy efficiency is mentioned in connection with sensors, which are the key enablers of the IOT technology (Tang, et al., 2024).

The green cluster (17 keywords) groups the features and potential challenges of BTA. They are data integrity, data security, (transaction) immutability, decentralisation and transparency of transactions. These properties would allow interoperability of the parties of the agri-food supply chain, giving them a competitive advantage. Vulnerability and security concerns are also mentioned in connection to blockchain-related methodologies. The public blockchain is the solution most often cited, as it is by definition accessible to any party. Apart from the QR code, often used to identify items in a blockchain, this cluster identifies the methods used to perform block validation, also known as the consensus mechanism, are proof of work, proof of stake, and proof of authority.

The blue cluster (15 keywords) summarizes the connection between BTA with other major issues related to food supply: food security, food waste, circular economy, productivity. The perceived impact of the BTA is achieving better nutrition, removing information asymmetries between buyers and sellers at different stages of the supply chain, and lowering corruption. However, there are environmental concerns due to the heavy use of energy by the blockchain technology, and a perception that BTA could improve sustainability through better management of the water resources used in the process via disseminating information on their potential contamination. The issues draw the question of acceptance of this technology, which is perceived as having potential negative effects on the environment.

The light lime cluster (15 keywords) groups the specific advantages of BTA implementation. There are benefits in food quality achieved by ensuring a better control the origin, movement and storage conditions of the food items, with positive effects on the prices and the willingness to pay of the potential customers. Most of these benefits are mentioned in connection to the wine industry and potato, which appears to have benefitted the most from blockchain solutions at the time of writing this article.

The indigo cluster (10 keywords) concentrates of brought by perceived benefits of a BTA system. They include prevention of harmful practices such as fraud and adulteration and, and ensure a better, timely response to adverse events such as outbreaks, contamination and supply disruption, through higher flexibility, operational efficiency and resilience compared to existing food supply systems, which increase trust and alleviate uncertainty about the food supply. What is notable is that blockchain technology can also benefit small-scale agri-food operations to the same extent as the major operators, thus improving their competitiveness and increasing the degree of resilience of the entire food network.

The turquoise cluster (10 keywords) groups the foodstuffs for which BTA implementations have been documented: cheese and dairy products, fruits and vegetables, meat, milk, and turkey. They are reported to have increased availability and variety of these foods.

Table 1 provides information on the main product-specific implementations that appear in our corpus of selected papers, which are indirect references, cited by other review papers.

Table no. 1. Main food-specific BTA implementations

Product	**Reference**
Coffee	Thirukumaran, Pryia, Raja, et al. (2024), Giganti, et al. (2024)
Shrimp	Thirukumaran, Pryia, Raja, et al. (2024)
Mango	Thirukumaran, Pryia, Raja, et al. (2024)
Turkey	Thirukumaran, Pryia, Raja, et al. (2024), Patel, et al. (2023)
Tuna	Thirukumaran, Pryia, Raja, et al. (2024), Giganti, et. al, (2024) Patel, et al. (2023)
Olive	Thirukumaran, Pryia, Raja, et al. (2024), Giganti, et al. (2024)
Beef	Thirukumaran, Pryia, Raja, et al. (2024), Giganti, et al. (2024) Patel, et al. (2023)
Chicken	Thirukumaran, Pryia, Raja, et al. (2024)
Milk	Thirukumaran, Pryia, Raja, et al. (2024), Giganti, et al. (2024)
Palm oil	Thirukumaran, Pryia, Raja, et al. (2024), Giganti, et al. (2024)
Rice	Thirukumaran, Pryia, Raja, et al. (2024)
Cocoa	Giganti, et al. (2024)
Dairy	Giganti, et al. (2024), Patel, et al. (2023)
Cotton	Giganti, et al. (2024)
Wool	Giganti, et al. (2024)
Tea	Giganti, et a. (2024)
Wine	Giganti, et al. (2024)
Livestock	Giganti, et al. (2024)
Honey	Giganti, et al. (2024)
Fish	Giganti, et al. (2024)
White sugar	Giganti, et al. (2024)
Extra virgin olive oil	Patel, et al. (2023)
Palm	Patel, et al. (2023)
Pork	Patel, et al. (2023)
Seafood	Sri Vigna Hema and Manickavasagan (2024)
Eggs	Thirukumaran, Pryia, Raja, et al. (2024) Giganti, et al. (2024)
Fresh fruits and vegetables	Thirukumaran, Pryia, Raja, et al. (2024)

The second co-occurrence structure is indeed enhancing the understanding of BTA, however, it does not give a full picture of the practical use cases. Wine industry appears to be the most well-known BTA (Chiaraluce, et al., 2024). Fish, aquaculture and seafood supply chains are benefit greatly from BTA as the freshness and product origin are critical for food safety (Chiaraluce, et al., 2024). Olive oil is another product where BTA can bring about significant benefits in terms of fraud detection, improved traceability and origin certification for extra-virgin products (Chiaraluce, et al., 2024). Real-time implementations comprise fresh fruits and vegetables, where real-time information is essential, meat and poultry, where origin and quality assurance is essential, and grains and cereals (Hema and Manickavasagan, 2024).

Conclusions

The scoping review conducted highlighted the knowledge landscape regarding the implementation of blockchain technology in agriculture, providing an overview of the most recent publications in the field, as well as a starting point for any directed research on this topic.

Findings have given a balanced picture of most topics that occur in conjunction with the adoption of blockchain technology, whose implementation and adoption goes hand in hand with other Agriculture 4.0 technologies: IOT, sensor technology, AI and ML, robots and cobots. The connection with IOT technologies seems to be the strongest and the most documented, as it ensures that blockchain ledger data is being matched with real-time information about the state, storage and movements along the food supply chain, often with the help of specialized sensors.

Implementing a blockchain solution is an extremely complex process, given the complexity and particular features of the technology. Many implementations use, or consider using the Ethereum blockchain due to its ability to implement smart contracts. Smart contracts are programmes which can be inserted in the blockchain which are able to seamlessly match supply and demand at each and every step of the agri-food supply chain. However, there are many concerns whether its implementation as a public blockchain is feasible. Smart contracts require specialized programming skills, which reduce the acceptance of a BTA solution, unless user-friendly frontend apps are designed to allow the use of the network by all participants in the agri-food supply chain, from farmers to end consumers (Patel et al., 2023).

There is a wide range of benefits associated with BTA. They ensure better certification, traceability, and ownership of the products, which produce benefits in terms of reducing information asymmetries, instances of fraud, adulteration, and corruption, while increasing reliability, resilience and improved efficiency of the agri-food supply chain. These benefits may help better address and contain the effects of adverse developments such as outbreaks, food shortages, price increases, while increasing consumer trust and willingness to pay for safer, more diverse, and certified products.

However, there are question marks concerning the sustainability of a BTA implementation. The perceived benefits in efficiency, transparency and trust, which translate in lower storage and distribution costs, may be offset by high energy costs required to operate the blockchain solution. To this, development costs for smart contracts and frontend apps need also to be considered, along with a framework that ensures decentralization and transaction

immutability compatible with the legal requirements of a highly regulated industry. Nevertheless, perceived benefits in ensuring a more sustainable agricultural production, reduction of food waste, improved food security, integration with a circular economic framework, and resilience achieved though decentralization of supply which allows for a bigger role through easier participation of small producers and SMEs in the agri-food supply chain have the potential to outweigh the implementation costs.

Limitations of these conclusion relate to a perceived lack of documentation of existing use cases, practices and policy efforts to implement blockchain solutions, and the uncertainty of the early stages of diffusion of this novel technology. Given that almost all of the literature focuses on a 9-year time periods (2016-2024), implementations are at an early stage, covering parts of the agri-food chain. The research documented in the research articles is focused on food chain characteristics is either following or documenting existing implementations, with the exception of IT articles that propose adaptations of blockchain technology. Thus, it is extremely difficult to rigorously identify existing research biases, and potential gaps seem obvious when considering the relatively fragmented information, partial in nature given by the relatively few implementations that are, in many cases, in an early stage.

All these considerations reveal the necessity and timeliness of conducting this scoping review which, through the comprehensiveness and diversity of the information synthesized, which constitutes its purpose (Gottlieb et al., 2021), is intended to provide a snapshot of the landscape as a guide for future research in the field of BTA, as more evidence and best practices will become available and help establish blockchain as a viable solution towards improving efficiency, sustainability and resilience of the agri-food supply chain.

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