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RESEARCH PAPER

Digital Transformation of Food Supply Chain Management Using Blockchain: A Systematic Literature Review Towards Food Safety and Traceability

Marios Vasileiou · Leonidas Sotirios Kyrgiakos · Christina Kleisiari · Pantelis Z. Lappas · Christos Tsinopoulos · Georgios Kleftodimos · Amalia Ntemou · Dimitrios Kateris · Christina Moulogianni · George Vlontzos

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Abstract The globalization of contemporary Food Supply Chains (FSCs) has introduced complexities involving multiple actors, food product transportation, and diverse information. Traditional information systems in FSCs face challenges in ensuring transparency and traceability due to the inherent complexities of multi-actor involvement, global transportation, and diverse information, making it difficult to ascertain product origin and processes, exacerbating issues such as food loss, safety concerns, and financial hazards. Blockchain technology, in conjunction with ancillary technologies, offers potential solutions to these challenges. This systematic literature review endeavors to comprehensively explore the multifaceted dimensions of blockchain's role in FSC management, with an emphasis on food safety and traceability, across six thematic areas, each guided by distinct criteria. These areas include general information, FSC application, factors of

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M. Vasileiou (✉) · L. S. Kyrgiakos · C. Kleisiari · G. Vlontzos
Department of Agriculture Crop Production and Rural Environment, School of Agricultural Sciences, University of Thessaly, 38446 Volos, Greece
e-mail: mariosvasileiou@uth.gr

L. S. Kyrgiakos
e-mail: lkyrgiakos@uth.gr

C. Kleisiari
e-mail: chkleisiari@uth.gr

G. Vlontzos
e-mail: gvlontzos@uth.gr

M. Vasileiou
Department of Economics, National and Kapodistrian University of Athens, 10559 Athens, Greece

P. Z. Lappas
Department of Statistics and Actuarial-Financial Mathematics, University of the Aegean, 83200 Samos, Greece
e-mail: pzlappas@aegean.gr

P. Z. Lappas · A. Ntemou
Netcompany-Intrasoft S.A., 2B Rue Nicolas Bové, 1253 Luxembourg, Märel, Luxembourg
e-mail: amalia.ntemou@netcompany.com

C. Tsinopoulos
Royal Holloway Business School, Royal Holloway, University of London Egham Hill, Egham, Surrey TW20 0EX, UK
e-mail: christos.tsinopoulos@rhul.ac.uk

G. Kleftodimos
CIHEAM-IAMM (Institut Agronomique Méditerranéen de Montpellier), 34090 Montpellier, France
e-mail: kleftodimos@iamm.fr

G. Kleftodimos
UMR MoISA, Univ Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, IRD, Montpellier, France

D. Kateris
Institute for Bio-Economy and Agri-Technology (iBO), Centre for Research and Technology-Hellas (CERTH), Dimarchou Georgiadou 118, 38333 Volos, Greece
e-mail: d.kateris@certh.gr

C. Moulogianni
Department of Agricultural Economics, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece
e-mail: kristin@agro.auth.gr

blockchain adoption, blockchain platform, ancillary technologies, and the related impact of blockchain adoption. From the 2097 documents found, 122 full-text articles were assessed, and 61 were included and classified in this study based on criteria. These criteria underscore blockchain's capacity for transparency, resilience, and sustainability in FSCs. The results further indicate that blockchain's integration within the FSCs has unveiled a tapestry of possibilities and considerations that underpin its transformative potential in business systems. Blockchain's inherent traits of transparency and immutability can enhance traceability, mitigate food fraud, and facilitate consumer trust, reshaping the information system's implementation in the FSC landscape. However, challenges such as integration complexities, data quality, scalability, and regulatory concerns should be addressed. Through these challenges, Artificial Intelligence (AI) arises as a potential solution complementing Blockchain. This amalgamation can effectively tackle certain existing obstacles, such as ensuring data accuracy and system compatibility, while providing stronger solutions for food safety and fraud prevention. The implementation of a comprehensive blockchain solution requires strategic collaboration, technological refinement, and regulatory alignment to fully realize its benefits and address the intricate management challenges of traditional FSC information systems.

Keywords Blockchain · Supply chain management · Food traceability · Food authenticity · Sustainability · Food fraud · Agri-food industry · Digital transformation · Artificial intelligence (AI) · Industry 4.0

1 Introduction

Contemporary Food Supply Chains (FSCs) have been extensively globalized, spanning across several countries and involving an increasing number of actors, extending the transportation of perishable goods, and intensifying the diversity of information inside FSCs. Consequently, the task of ascertaining the origin and production process of a particular product has become increasingly challenging, hence exacerbating the challenges associated with addressing concerns within FSCs. The intricate nature of FSCs presents several obstacles, including those related to food loss, food safety, and financial hazards across each stage (Li et al. 2021). According to a recent study conducted by McKinsey & Company, there is an approximate worldwide loss of food valued at $600 billion during or after the harvest process, with 33–40 percent loss of the world's food (Borens et al. 2022).

As Supply Chains (SCs) have gradually grown in complexity, there has been an increasing consumer need for enhanced transparency about product safety and authenticity (Wu et al. 2021). In today's world, consumers have the ability to access food products originating across diverse geographical locations, enabling the purchase of fruits and vegetables regardless of their seasonal availability or processed products with ingredients sourced from numerous regions around the globe (Li et al. 2021). Simultaneously, the trust of consumers in food labels has been undermined due to instances of food adulteration and mislabeling, encompassing intentional acts of replacement, dilution, counterfeiting, misrepresentation of food, ingredients, or packaging, as well as the dissemination of incorrect or deceptive information on the product (Köhler and Pizzol 2020). The yearly cost of this is projected to be between $30 and $40 billion, as stated in the World Economic Forum (World Economic Forum 2019), while certain instances of food fraud that have been exposed have resulted in heightened consumer vigilance. The revelation of significant incidents pertaining to food adulteration occurred in 2013, when the presence of horse meat was detected in several ground beef products across Europe and pesticide residues were found in food (European Union 2015; EFSA 2015); these two events were the catalysts for the European strategy to eliminate food fraud. In another study, conducted in Canada in 2018, it was shown that a significant proportion of seafood items, namely 44% out of a total of 382 samples, were mislabeled (Levin 2018). In light of the aforementioned factors, the demand for transparency and trustworthiness in the dissemination of information pertaining to the FSC has been steadily rising, and the digitalization of FSC operations is imperative in the contemporary world.

Amidst the increasing complexity of contemporary FSCs, traditional information systems have faced significant limitations in providing the required transparency, traceability, and security. Existing systems often struggle to keep pace with the dynamic and expansive nature of globalized FSCs, leading to gaps in information flow and hindering the effective monitoring of products through their entire lifecycle (Beck et al. 2017). The need for a transformative solution that can seamlessly integrate into the evolving landscape of FSCs has spurred the exploration of blockchain technology. There has been a growing academic focus on the utilization of this technology to address the challenges of traceability and trust within FSCs (Pearson et al. 2019; Cozzio et al. 2023). Blockchain (BC) aims to offer verifiable information about the SC and ensure that all relevant parties have access to this information. The utilization of BC within FSCs offers several advantages, including increased transparency, access to real-time product information, prevention of fraudulent activities, resistance to tampering, decreased operational expenses, improved traceability, enhanced product quality, assurance of safety and authenticity, and a more organized certification procedure (Yogarajan et al. 2023). The blockchain is an innovative digital ledger system characterized by decentralization, enabling the secure and immutable storage of data (Vu et al. 2023), and it was originally introduced as the underlying technology behind the cryptocurrency Bitcoin in 2008 (Risius and Spohrer 2017). Since then, BC has gained significant attention and found applications in various industries beyond cryptocurrencies. At its essence, a blockchain refers to a sequential arrangement of blocks, whereby each block encompasses a compilation of transactions or data. These blocks are interconnected through cryptographic hashes, therefore guaranteeing the integrity of the data, and providing a secure way to verify the validity of the information stored in the system (Galvez et al. 2018). Thus, these data exhibit the characteristics of immutability, transparency, traceability, and tamper-proofing. BC encompasses a comprehensive and verifiable ledger of all previous transactions, enabling the coordination of actions and the verification of events through its constituent blocks, while maintaining the confidentiality of the digital resources and individuals concerned (Dinesh Kumar et al. 2020). To mitigate the risk of unauthorized access, tampering, or compromise by third-party entities, this technique employs mathematical calculations that require significant processing resources for resolution. All things considered, BC, with its decentralized and immutable ledger, presents an innovative paradigm for information management within FSCs. By providing a secure and transparent platform, blockchain addresses the shortcomings of traditional information systems, ensuring that all relevant stakeholders have access to real-time and verifiable data. This shift towards blockchain technology is not merely a technological upgrade but a strategic response to the inherent challenges of contemporary FSCs, promising to revolutionize how information is managed, shared, and secured throughout the FSC.

Despite the perceived advantages of BC across several industries, its implementation remains challenging owing to its inherent complexity (Mavilia and Pisani 2022). FSC participants encounter persistent challenges when initiating the integration of BC into their operational processes. Significant obstacles, including technological, organizational, and regulatory hurdles, that limit the effectiveness of the FSC and hinder the implementation of BC have been identified in the literature (Rejeb et al. 2020). Nevertheless, BC has demonstrated its efficacy in several sectors, resulting in positive outcomes for those who have embraced it (Munir et al. 2022). The varying results regarding the effects of BC, particularly in the comparison between the agri-food sector and other industries, suggest that BC is still in its early stages of development within the agri-food industry (Yogarajan et al. 2023).

The adoption of BC in FSC is in its infancy and presents a multifaceted challenge, for which the literature has not yet offered a thorough comprehension of this subject matter. Hence, the establishment of a well-defined research framework is imperative, and researchers are contributing to the literature by conducting surveys with the aim of enhancing cognizance of this subject matter. This study utilizes Systematic Literature Review (SLR) as a methodological approach to examine and integrate existing research conducted on blockchain in FSCs regarding food safety and traceability. In Table 1, similar literature review studies in the field of BC in FSC are presented. This table quotes their contribution to the field, their shortcomings, and the number of articles analyzed.

This study contributes to the existing literature by performing a comprehensive SLR, adhering to rigorous steps and stages as outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines in contrast to the aforementioned studies. More precisely, this SLR highlights the gaps and limitations in the existing literature when implementing BC technology in agriculture. In addition, various criteria are employed that differ from those utilized in these studies on a different set of articles, while the sustainability principles are examined through the utilization of these criteria and specifically, economic, social, operational, environmental, and management. Furthermore, both Scopus and Web of Science (WoS) databases have been utilized to include the most significant articles to provide a wider range of high-quality articles. In a nutshell, this study addresses several shortcomings in previous research and offers a more robust and holistic understanding of the topic. These contributions are further quoted as follows:

- *Rigorous methodological approach* This SLR adheres to the PRISMA guidelines, ensuring a systematic and reproducible review process. This methodological rigor contrasts with previous studies, such as in Li et al. (2021), which lacked clearly defined exclusion criteria, or Rejeb et al. (2020), which did not classify the articles based on criteria, thereby enhancing the reliability and validity of the findings.
- *Comprehensive database coverage* This study incorporates both Scopus and WoS databases, unlike (Keogh et al. 2020; Tharatipyakul and Pongnumkul 2021; Yogarajan et al. 2023). This inclusion of multiple high-quality databases allows for a broader and more comprehensive collection of relevant articles, ensuring that the review encompasses a wide range of significant studies. Their indexing process encompasses a diverse selection of esteemed academic journals, guaranteeing

Table 1 List of recent systematic literature reviews regarding BC in FSC

References	Contributions	Shortcomings	No. articles analyzed
Li et al. (2021)	Identifies the benefits and challenges of BC in FCS Performs a synthesis analysis to explore the identified Highlights the BC visibility and transparency in FSC	Only 34 of the 74 articles included in the study are classified based on the criteria Exclusion criteria are not defined, so the work is not reproducible	74
Yogarajan et al. (2023)	Identifies eight themes for Blockchain Adoption Supports blockchain-based agri-food sector strategy and policy Highlights the significance of guidelines and policy-level engagement following the implementation of BC Indicates key factors driving blockchain technology adoption	Only WOS database was included, omitting the Scopus database on article retrieval Conceptual studies are excluded in this SLR Few articles are included in this study, so as to classify based on the criteria	27
Vu et al. (2023)	Identifies BC adoption drivers and barriers, applications, and implementation stages in FSC Identifies future research opportunities from BC barriers Develops a conceptual framework consisting of three stages for BC implementation	The criteria related to the impact of blockchain adoption were not considered The articles included in the study are not classified based on the criteria in any Table	69
Tharatipyakul and Pongnumkul (2021)	Identifies the target groups and the approaches for collecting and visualizing data Highlights that user involvement for evaluation is lower in blockchain-based studies than in non-blockchain-based ones Discusses the research gaps and future research directions related to user interface design	This article refrains from conducting evaluations on the interfaces, even when employing design heuristics Only Scopus database was included, omitting the WOS database on article retrieval The user interface was examined by manual inspection of the submitted screenshots, so aspects of the user interface could me omitted	64
Rejeb et al. (2020)	Highlights that blockchain is in its early developmental phase and holds significant potential for transformative and fundamental changes Discusses that blockchain has the potential to promote food traceability, foster collaborative partnerships within the FSC, optimize operational efficiency, and ensure the sustainability of food trade operations Identifies the drawbacks associated with blockchain technology encompassing three distinct areas, technological, organizational, and regulatory impediments	Only Scopus database was included, omitting the WOS database on article retrieval The articles are not classified based on the conceptual framework presented in any table SLR criteria are not identified as defined by SLR guidelines	61

that the review incorporates studies of exceptional quality and relevance.

- *Multi-dimensional criteria* This study employs a set of thematic areas (6) and criteria (20) that differ from those used in previous studies, extending up to sustainability principles across economic, social, operational, environmental, and management dimensions. This multi-dimensional approach provides a more thorough examination of blockchain technology's impact on FSCs, highlighting aspects that were not previously explored in detail.
- *Identification of research gaps* By highlighting the gaps and limitations in the existing literature regarding the implementation of blockchain technology in agriculture, this study provides a clearer understanding of the areas that require further research. This identification of research gaps is crucial for guiding future studies and advancing the field.
- *Holistic insight into sustainability* This study examines sustainability principles, providing a nuanced understanding of how blockchain technology can contribute to the sustainability of FSCs. This holistic perspective contrasts with the narrower focus of previous studies and offers valuable insights into the broader implications of blockchain adoption.
- *Thematic analysis and structured classification* The study categorizes articles across six thematic areas: general information, FSC application, factors of

blockchain adoption, blockchain platform, ancillary technologies, and the related impact of blockchain adoption. This structured classification provides a detailed and organized understanding of the diverse aspects of blockchain technology in FSCs, surpassing the thematic scope of previous studies.
- *Enhanced understanding of blockchain's transformative potential* By systematically integrating existing research, this study underscores blockchain's capacity to enhance transparency, traceability, and resilience in FSCs. It emphasizes blockchain's potential to mitigate food fraud, facilitate consumer trust, and promote sustainability, thereby offering practical implications for stakeholders in the FSC ecosystem.

The remainder of the paper is organized as follows: In Sect. 2, the methodology of this study is presented, while in Sect. 3, the results along with the criteria examined throughout the SLR procedure are discussed. In Sect. 4, the limitations and gaps of BC are presented, while Sect. 5 concludes the paper.

2 Materials and Methods

When investigating a certain research issue, subject, or phenomena, a SLR can be conducted to locate, appraise, and evaluate all relevant studies (Snyder 2019). This methodology is gaining popularity since it adheres to a thorough and auditable protocol that enables the evaluation of accessible studies pertinent to a certain subject (Xiao and Watson 2019). Moreover, it allows for the discovery of unfilled study areas in existing studies, which may then be explored in future work (Kitchenham and Charters 2007; Ko and Comuzzi 2023).

This study utilizes SLR under the PRISMA guidelines (Page et al. 2021) as a methodological approach to examine and integrate existing research conducted on Blockchain in FSCs towards food safety and traceability. PRISMA provides a structured approach to literature reviews, emphasizing transparency in the selection process, data extraction, and synthesis. This ensures that the review is thorough and reproducible, which is crucial for maintaining the credibility of the findings. PRISMA guidelines was chosen as it aligns with the study's objectives, particularly the focus on transparency and reproducibility. Given the interdisciplinary nature of blockchain technology in FSCs, PRISMA's comprehensive framework was deemed suitable for capturing the multifaceted aspects of the research.

A preliminary search was performed using Scopus and WoS databases to identify significant clusters to guide this study, and by using the terms "blockchain" and "food supply chain", 5345 results were found (4829 and 516, respectively). These databases were selected as the primary databases for the systematic literature review due to their comprehensive coverage, high-quality indexing, and relevance to academic research. Both databases are widely recognized for their extensive collections of high-quality coverage of academic publications across various disciplines. They index a wide range of reputable journals ensuring that the review includes high-quality and relevant studies. In order to identify the complete survey term set and reduce the total results, these results were exported and fed to VOSViewer software (Waltman and Ecken 2010). Figure 1 presents the outcome of this software, which illustrates three distinct clusters: *(i)* blockchain – food supply – supply chains, *(ii)* blockchain – food supply chain – traceability, *(iii)* food supply – food safety – food traceability. In light of this, the final terms selected were "blockchain", "food supply chain", "traceability", and "safety", as they were the most common terms that match to our survey.

By focusing the search on these four terms ("blockchain", "food supply chain", "traceability", and "safety"), the results were narrowed down to 2097 (Scopus = 1935 + WoS = 162). Given the fact that this search is based on full articles, many articles were not relevant to this research, and therefore the search was restricted to the article's title, abstract, and keywords, leading to 252 articles for screening (Scopus = 124 + WoS = 92). Subsequently, the duplicates were removed (33), the non-English articles were excluded (10), and the search was limited to final journal articles and conference papers, leading to 122 articles for full-text assessment. The final search queries of both Scopus and WoS are given in Appendix A (available online via http://link.springer.com). Based on the full-text assessment, 54 articles were included in this research, along with 7 publications that were found using snowballing (Wohlin 2014). The inclusion criteria focused on selecting studies that presented significant and relevant content specifically addressing the application of blockchain technology in FSCs. Articles that lacked substantial information, detailed analysis, or empirical data on the role of blockchain in enhancing food safety and traceability were excluded. Both qualitative and quantitative studies were considered, provided they offered meaningful insights into blockchain implementation, challenges, and benefits within FSCs. Figure 2 summarizes the SLR methodology, under PRISMA guidelines (Page et al. 2021).

The scope of the search with respect to the publication year was not specified, as the articles included in the search were published after 2016, indicating an exponential increase up to 2023, as shown in Fig. 3. The search was conducted on 24th October 2023, hence including articles up until that date within the year 2023.

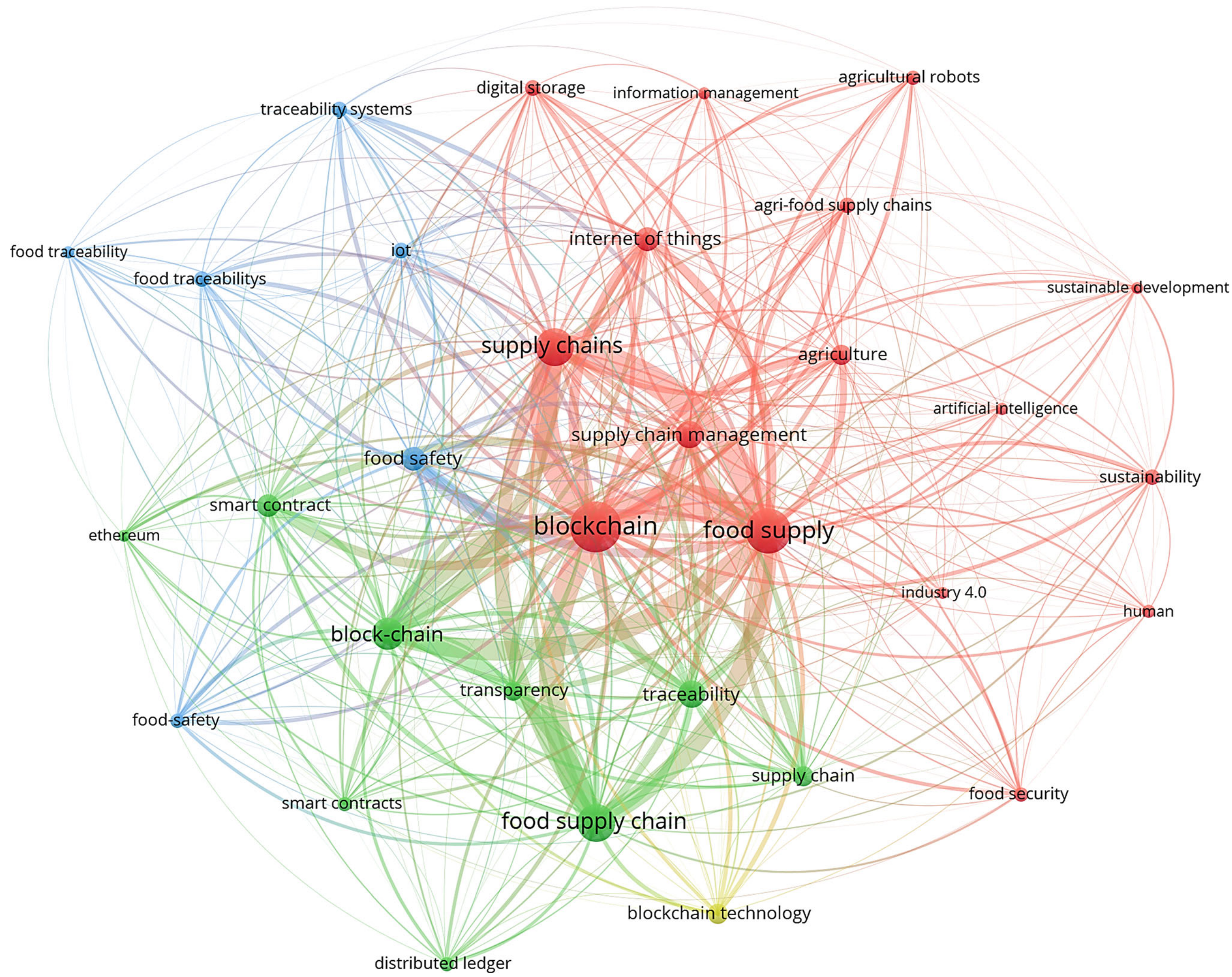


Fig. 1 Relationship of the keywords regarding "food supply chain" and "blockchain"

3 Results and Discussion

The purpose of this review is to enhance the understanding of the impact of BC implementation in the FSC by offering comprehensive views derived from current literature. During the review process of the selected articles, six primary areas were identified, which center upon various aspects of blockchain implementation in the FSC. These areas include the general information of the articles, FSC application, factors of BC adoption, BC platform utilized, ancillary technologies utilized, and the related impact of BC adoption, as shown in Fig. 4.

The selection of these thematic areas follows the logical structure of a study or a research article, ensuring a systematic and thorough exploration of blockchain technology in FSCs. Beginning with General Information, the review sets the context and background for the study. FSC Application then delves into the specific use cases and practical implementations, akin to the methods followed. Factors of blockchain adoption examine the drivers, motivations, and barriers. Blockchain Platform details the technologies used to implement in a study. Ancillary Technologies explores supplementary technologies parallel to the main platform. Finally, the related impact of blockchain adoption assesses the broader implications, analogous to the implications of a study. This structured approach ensures a comprehensive and coherent review, mirroring the progression and depth of a well-organized research. These areas were segmented into criteria by which the articles were categorized. Table 2 quotes these criteria with their descriptions.

3.1 General Information

In the category of general information, four main criteria of the articles are analyzed: *(i)* the publication year, *(ii)* the publishing company, *(iii)* the source type, and *(iv)* the document type. Most of the documents reviewed were

Fig. 2 SLR methodology using PRISMA guidelines

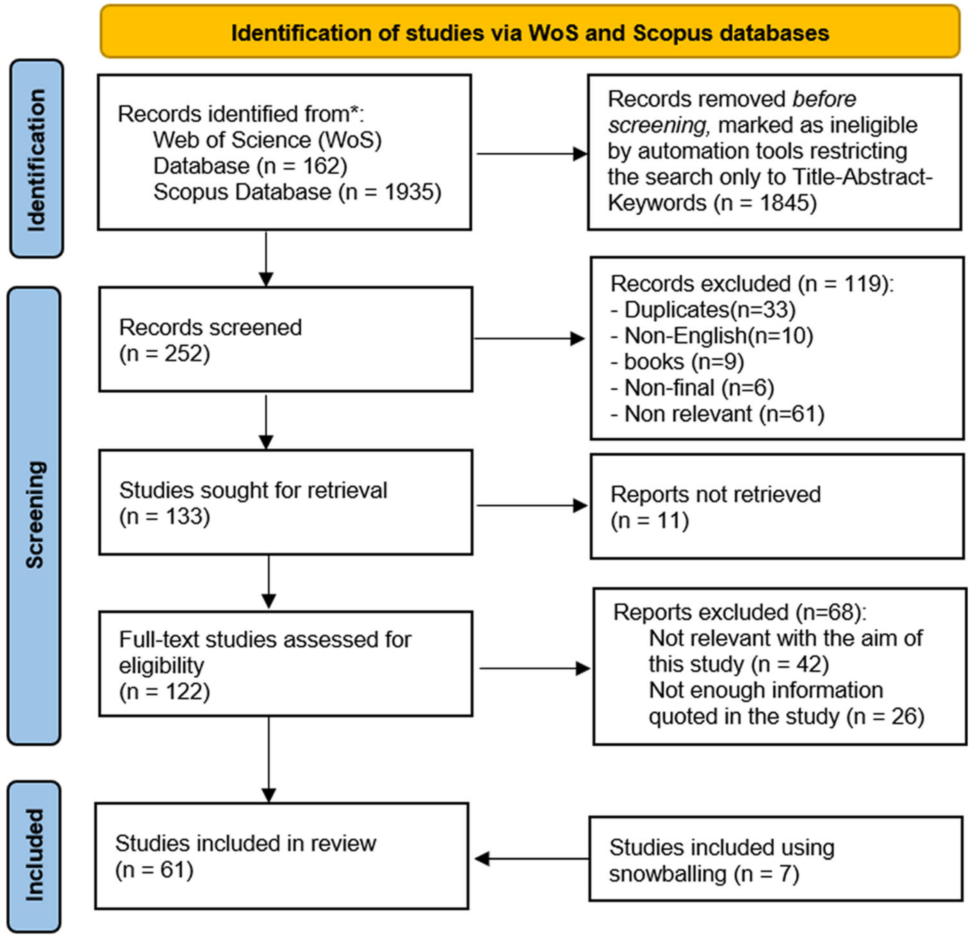
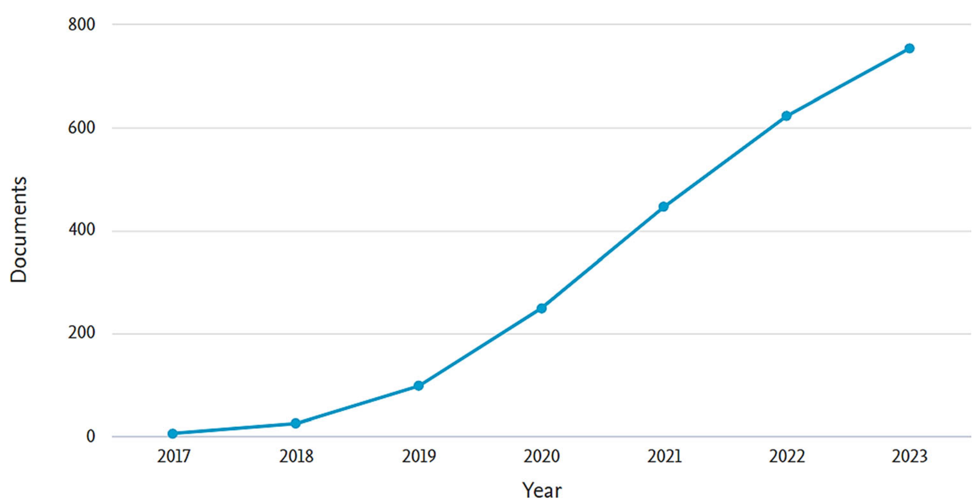


Fig. 3 Publications per year regarding the four terms in the initial search



journal articles (46), while a few high-quality conference papers (15) that presented comprehensive work were considered. The majority of publications included in the study were from 2022 (23) followed by those published in 2023 and 2020 (10), as shown in Fig. 5.

Regarding the publishing company information, Fig. 6 visualizes the number of documents per publisher in this study, classified by their source type. The publishers with less than 3 documents in this study were added to the category "Other". The publisher with the most journal articles in this study is MDPI (15), while the majority of conference papers were published in the IEEE (10).

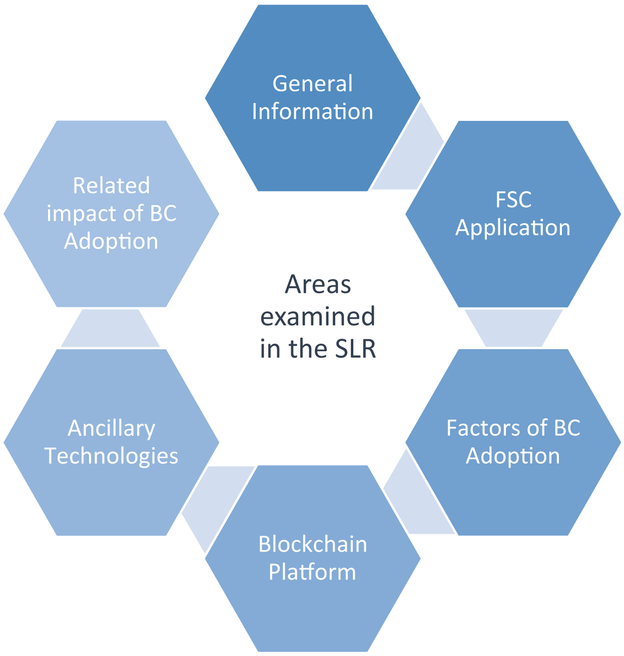


Fig. 4 Areas examined in the SLR

In addition, the documents were classified based on their content type, which included frameworks (37), case studies (8), and conceptual frameworks (16) (Fig. 7).

3.2 FSC Application

The utilization of blockchain technology within the FSC has noteworthy academic significance, due to its potential to address critical challenges within this sector. The integration of BC into various sectors of the FSC is characterized by nuanced implementations driven by sector-specific attributes, challenges, and requirements.

Within the domain of perishable goods such as dairy products and fresh produce, the emphasis lies on traceability and safety (Casino et al. 2020). Given their limited shelf life, it is imperative to implement efficient and precise monitoring systems for these commodities in order to safeguard their quality and authenticity (Tan and Ngan 2020). Dairy products represent a significant portion of consumable food products and are widely recognized as a fundamental source of nutrition throughout many age cohorts (Niya et al. 2021). Nevertheless, the nutritional content and presence of hazardous compounds in milk can be compromised by adulteration and contamination, rendering it unsuitable for consumption and potentially harmful. The prevalent adulterants found in milk are water, urea, detergents, starch, vanaspati, glucose, and preservatives (Khanna et al. 2022). On the other hand, non-perishable goods such as grains or oil might prioritize blockchain's traceability for quality assurance and fraud prevention, as their longevity allows for a different perspective on tracking (Zhang et al. 2022).

Supply chain complexity also shapes the application of blockchain. Highly intricate SCs, commonly associated with processed foods featuring multiple ingredients, utilize BC to systematically monitor the source and characteristics of each constituent (George et al. 2019). Grain and oil FSCs have, also, multifaceted structure, characterized by protracted turnover cycles and a multitude of stakeholders, so rendering the preservation of its security a formidable task (Zhang et al. 2022; Xu et al. 2022). Conversely, more streamlined SCs pertaining to commodities such as rice prioritize the provision of precise origin details as a means to achieve transparency, while avoiding the intricacies associated with several middlemen (Akazue et al. 2023). In addition, geographical considerations further influence implementation choices. Products with specific geographic origins, like specialty cheeses or wines, capitalize on BC to validate claims related to Protected Designation of Origin (PDO) or Protected Geographic Indication (PGI) (Vasileiou et al. 2024a). In addition, regulatory compliance has a significant impact on FSCs. Highly regulated products, such as dairy, rely on BC to streamline documentation and ensure adherence to strict quality and safety standards (Niya et al. 2021).

In essence, the utilization of BC across several sectors of the FSC highlights the versatility of this technological advancement. While the fundamental advantages of transparency, traceability, and authenticity remain consistent, the distinct attributes of certain sectors influence the strategic use of BC to address specific challenges and seize on opportunities, including the length and complexity of the product's SC, the risk factors associated with different products, and the ability to verify authenticity and safeguard against food fraud. The application of blockchain across various segments highlights the adaptable nature of this technology to cater to diverse needs. The sectors included in this study found in the articles reviewed are rice, dairy, grain, coffee beans, oil, meat, apples, soybeans, herbs, and olives; to a degree, they can be seen in Fig. 8.

Furthermore, the implementation of BC in the FSC exhibits notable variations among different countries, reflecting the distinctive socio-economic, regulatory, and cultural contexts within which these systems operate. Regulatory frameworks and compliance requirements emerge as prominent factors influencing BC implementation (Thanujan et al. 2021). Countries with stringent regulations pertaining to food safety and origin labeling, such as the European Union (EU) and the United States of America (USA), incorporate BC as a means to meet and exceed these regulatory standards (Yeoh 2017). This often involves a comprehensive monitoring of every phase within the FSC, hence making blockchain's unalterable

Table 2 Summary of the criteria examined throughout the SLR procedure

Category	Criteria	Description
1. General information	Year	The publication year of the article
	Publisher	The name of the Publisher (counted only those that appeared at least in 3 articles
	Source type	Journal or Conference paper
	Document type	Framework, Case study, or Conceptual Framework
2. FSC application	Industry	FSC Industry (e.g. Diary, Rice…)
	Country	Country of origin of the study that implemented BC
3. Factors of BC adoption	Transparency and traceability	There is a need for enhanced traceability of the products in the FSC of the study
	Food safety and quality	There is a need for assurance of food safety while preventing food fraud and food adulteration
	Security and trust	There is a need to increase the security of the legend system
	Consumer demand for authenticity	There is a need to increase trust with consumers and provide them with the ability to authenticate the products journey in the SC
4. Blockchain platform	–	Type of distributed ledger software (e.g. Ethereum, Hyperledger)
5. Ancillary technologies	IoT	The integration of IoT devices, sensors, and other data sources enables the comprehensive monitoring of a product's journey
	Smart contracts	Smart contracts facilitate the automated execution of predetermined rules and agreements inside the blockchain system
	QR code	A QR code is a two-dimensional barcode that can store information in a machine-readable format. QR codes are placed on food packaging, labels, or tags
	App for consumers	A binary field that specifies whether the article has studied the BC as a service to consumers. Usually, customers have access to BC data through a Quick Response (QR) code labeled on the product. Through the utilization of BC and a respective app, consumers can authenticate the provenance, quality, and management of food items
6. Related impact of BC adoption	Technological	The article examines the implications of technological progress
	Social	The impact that the article presents pertaining to customers or society in general
	Economic	The article takes into consideration the economic impact of the BC adoption
	Environmental	The impact on the environment is considered, such as reductions in emissions and optimization of operations that have a general effect on the environment
	Management	The article examines the impact on business and SC management

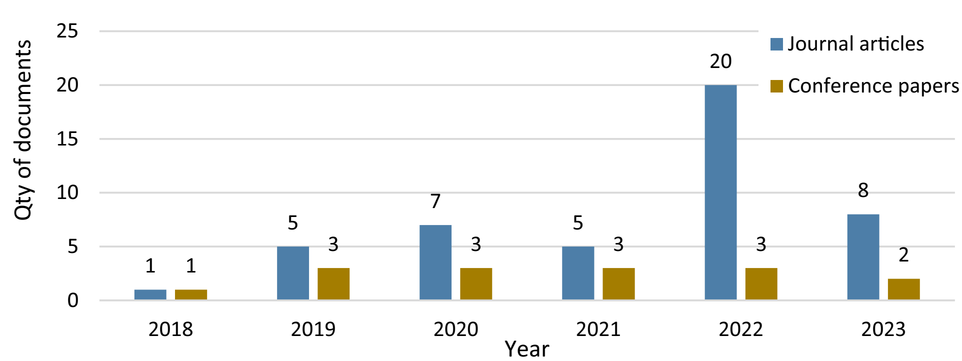
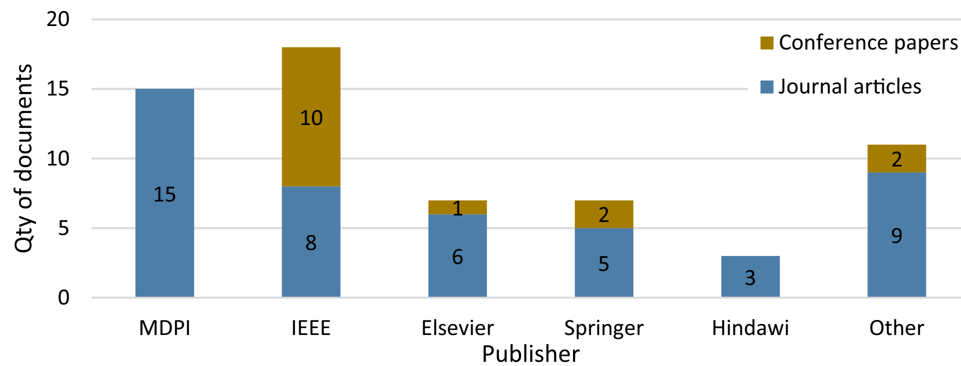


Fig. 5 Year-wise and source-type publications included in this study

ledger an appealing instrument for effortless adherence to regulations.

In addition, the level of technological infrastructure and digital literacy within a country significantly shapes blockchain adoption (Kavut 2021). Developed nations with matured economies, characterized by strong technical ecosystems, demonstrate a higher propensity to use blockchain technology inside their respective FSCs. On the other hand, developing nations may encounter difficulties

Fig. 6 Number of documents per publisher in this study, classified by their source type



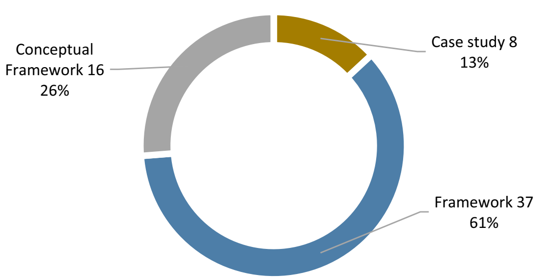


Fig. 7 Documents classified based on their content type

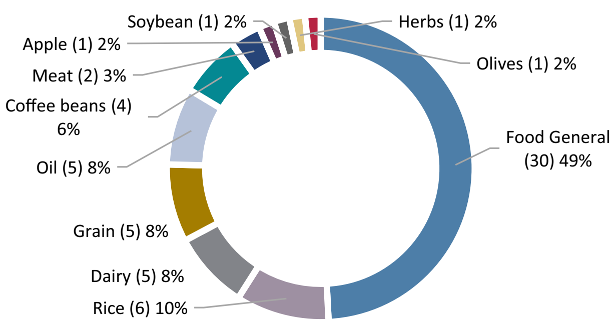


Fig. 8 Industry of BC application

in using blockchain technology, as a result of constraints in terms of connection and technological capabilities.

Given the significance of the country of origin, in the context of the BC application, it is crucial to consider the countries that were reported in the publications listed (Fig. 9).

3.3 Factors of BC Adoption

The elongation and complexity of SCs can lead to a decrease in traceability and transparency, hence raising the potential for fraudulent activities and diminishing customer trust (Garaus and Treiblmaier 2021). Simultaneously, the recent Covid-19 pandemic has led companies around the world to restructure and change the way they think and operate in an increasingly volatile and uncertain global environment (van der Aalst et al. 2020). In this subsection, the challenges related to FSCs along with the necessity of BC adoption are discussed. The adoption of BC in the context of FSC stands as a consequential development that holds profound implications for the effective management and transformation of this intricate domain. Its implementation addresses multifaceted challenges, ranging from traceability, transparency, and security to food safety and authenticity, while retaining consumers trust. Table B1 in Appendix B classifies the articles reviewed in this study, pertaining to the factors of BC adoption. More specifically, this table includes all the articles reviewed, with their respective information regarding the country of origin of the framework, the industry of application and the main

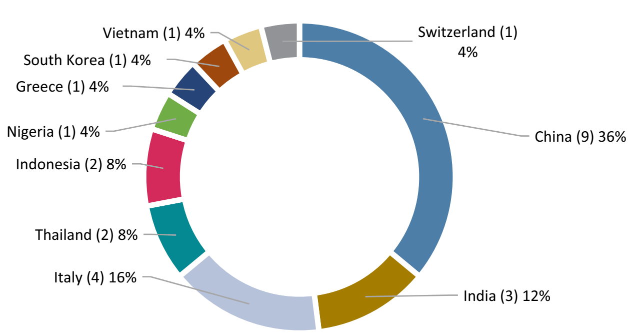


Fig. 9 FSC countries of the reviewed studies

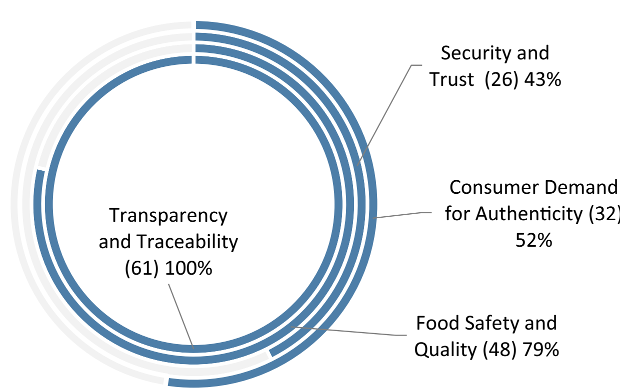


Fig. 10 Quantity of articles referring to the four factors of adoption

factors discussed of blockchain adoption. Furthermore, Fig. 10 quantifies these articles by referring to the four factors.

3.3.1 Transparency and Traceability

The fundamental focus of BC adoption centers around performance expectancy, traceability, and transparency (Ghode et al. 2020; Dehghani et al. 2022). The FSC is characterized by its intrinsic complexity, marked by numerous intermediaries and intricate processes (Katsikouli et al. 2021). This intricacy has consistently presented difficulties in effectively monitoring the origins, the transportation, and the transformations of food products (Tanwar et al. 2022). BC promises to surmount these challenges, by enabling a comprehensive and accessible record of a product's journey, thus empowering stakeholders with an unprecedented level of insight into the origin and path of food products (Dinde and Shirgave 2023). Consequently, the implementation of BC provides regulatory authorities and SC participants with timely and valuable information, in situations involving recalls or contamination issues. This enables them to make educated decisions and respond effectively.

In the literature, researchers underline the criticality of establishing a traceability system that enables the tracking of products from the early production stages to the end user (Hayati and Nugraha 2018; Casino et al. 2019; Dong et al. 2020; Dinde and Shirgave 2023). This traceability system plays a pivotal role in safeguarding consumer health, hence exerting a substantial influence on the success of enterprises involved (Balamurugan et al. 2022). The utilization of a traceability system is advantageous for items that possess a greater vulnerability to contamination, such as pharmaceuticals, dairy products, and meat (Bayramova et al. 2021). In situations when there is an increased likelihood of contamination, the implementation of a traceability system serves to provide transparency within the production and operating procedures (Menon and Jain 2022). A case study in the diary sector is introduced in (Casino et al. 2020), utilizes BC as a method for establishing a chain of custody. Additionally, smart contracts serve as an automated tool for overseeing stakeholders and activities related to SCM, incorporating a collection of services that provide a comprehensive traceability process, spanning from the procurement of raw materials through the delivery of final products to clients (Egelund-Müller et al. 2017). In this SLR, all the studies highlight transparency and traceability as a factor of adoption (Fig. 10).

3.3.2 Food Safety and Quality

The second factor pertains to food safety and quality, which encompasses the proper handling, processing, and hygienic storage of food to mitigate the risk of infection while preserving the product's quality. Modern FSCs are often complex and global, involving multiple intermediaries and long distances. This complexity increases the chances of mishandling, delays, and information gaps, making it difficult to trace the source of contamination or quality issues (Qian et al. 2020). The risk of contamination by pathogens (e.g., bacteria, viruses) during production, processing, transportation, and storage can lead to foodborne illnesses (Tao et al. 2022). In addition, some regions lack the necessary infrastructure, including cold storage facilities and transportation systems, to maintain the quality and safety of perishable food items (Kayikci et al. 2022a). Maintaining proper temperature throughout the SC is crucial, especially for perishable goods, while temperature fluctuations can compromise food quality and safety.

Furthermore, the complexity of the contemporary FSC, along with the lack of traceability, presents a formidable obstacle to effectively monitoring the flow of food items across the SC (Thangamayan et al. 2023). Consequently, this creates a favorable environment for fraudulent products to infiltrate the market without being identified (Balamurugan et al. 2022). Food fraud refers to the intentional act of deceiving consumers about the content, origin, or quality of food products for economic gain (Manning 2016). It can occur at various points in the SC and presents significant challenges to the food industry concerning food safety. According to a study (Kramer et al. 2021), the adoption of BC in the agri-food industry is significantly influenced by concerns related to food safety. As stated in (Kayikci et al. 2022b), the implementation of BC in the agri-food sector has witnessed a notable surge, due to the capability of BC to identify and mitigate contamination or food fraud within the SC, as well as its potential to expedite product recalls. In this SLR, 79% (48) of the studies highlight food safety and quality as a factor of adoption (Fig. 10).

3.3.3 Security and Trust

The increasing intricacy of FSCs and the growing ecosystems necessitate a heightened level of trust, security, and openness compared to previous times. Consumers demand transparency and assurances that the data provided are true and accurate (Iftekhar and Cui 2021). The security aspects of blockchain, such as cryptographic encryption and distributed consensus, contribute to the establishment of a robust degree of data security and trust (Chatterjee and Singh 2023). Ensuring security is of utmost importance in an industry, where the occurrence of data breaches and unauthorized access poses a significant risk to the confidentiality of sensitive information.

Conventional SC systems have encountered challenges pertaining to vulnerabilities associated with breaches of data security, unauthorized alterations, and instances of fraudulent behavior (Menon and Jain 2022). The implementation of BC serves as a preventive measure against data alteration, hence enhancing security. For instance, a study proposes a decentralized framework as a solution to address several types of fraud, present in the current centralized system (Akazue et al. 2023). It aims to reduce corruption by using a sensor-based layered model and minimize inaccuracies in reported data along the value chain.

3.3.4 Consumer Demand for Authenticity

In contemporary society, consumers who possess a high level of awareness and responsibility, actively pursue comprehensive and intricate knowledge pertaining to the origins, manufacturing processes, and ethical standards associated with the goods they choose to consume. The utilization of BC allows companies to effectively disseminate information and verify assertions of validity, therefore adapting to the specific interests of consumers (Treiblmaier and Garaus 2023). In a study of 350 participants, two significant advantages of BC implementation were identified: origin verification and the enhancement of product trustworthiness (Tharatipyakul et al. 2022). The integration of trustworthiness verification mechanisms, including traditional methods, in BC systems is expected to enhance their overall efficacy and advantages of BC.

In addition, food labeling and authenticity regulations and standards differ among nations and regions, leading to challenges in implementing uniform measures to combat food fraud on an international level (Behnke and Janssen 2020). Food authenticity refers to ensuring that the food products, available in the market, are genuine and correctly labeled with accurate information about their origin, composition, and quality (Katsikouli et al. 2021). The concept of food authenticity is commonly seen as a state, rather than a deliberate action (Robson et al. 2021). Counterfeit products, fraudulent labeling, and misrepresentation of product attributes have historically compromised consumer trust and safety (Garaus and Treiblmaier 2021). Blockchain's cryptographic and consensus mechanisms establish a safeguard against such malpractices. By rendering records tamper-proof and auditable, blockchain imbues products with a digital identity that validates their integrity and origin. This facet resonates, profoundly in sectors where geographic specificity is emblematic of product value, exemplifying blockchain's ability to reinforce the ethos of authenticity (Contini et al. 2023). In other words, BC provides customers with a high level of assurance, regarding the provenance and transparency of products, while participants possess the capability to retrieve the transportation and storage records pertaining to their products (Pranto et al. 2021). In this SLR, 43% (26) of the studies highlight security and trust as a factor of adoption (Fig. 10).

3.4 Blockchain Platform

Within the dynamic landscape of BC several prominent platforms have emerged as significant contenders, each representing unique paradigms and fulfilling diverse roles within the wider blockchain ecosystem (Zheng et al. 2018). In this study, two prevailing BC platforms have been identified in the literature, Hyperledger and Ethereum, each distinguished by its unique characteristics, intended applications, and architectural approaches. These platforms have attracted considerable attention, in the field of blockchain technology, due to their ability to cater to various business requirements, spanning from enterprise apps to Decentralized Applications (DApps) (Cai et al. 2018).

Hyperledger is a collaborative open-source initiative fostered by the Linux Foundation. It offers a wide range of blockchain frameworks, tools, and standards, therefore providing a full suite of resources, while mostly operating inside the boundaries of permissioned or private blockchains (Gao et al. 2020). This architectural decision facilitates regulated engagement, making it especially appropriate for consortia and business environments. The modular design of Hyperledger is a prominent characteristic that provides businesses with the ability to pick components according to their individual needs, hence enabling customization of the technology. Moreover, the prioritization of data confidentiality and privacy is a distinguishing characteristic of Hyperledger, rendering it a favored option for sectors that necessitate safeguarding sensitive information (Agrawal et al. 2022). In a study, a prototype has been developed utilizing the Hyperledger Fabric Blockchain framework (Vo et al. 2021). The authors claim that the utilization of BC presents the potential to enhance both efficiency and security within the food supply chain management system, in contrast to conventional systems that rely on a client–server architecture. Another study presents a novel system architecture for the complete grain SC, utilizing BC and a multimode storage mechanism that integrates chain storage (Zhang et al. 2020). The proposed solution exhibits several distinguishing features in contrast to predecessors, including data security and dependability, improved information connectivity and intercommunication, real-time exchange of hazardous-material information, and a dynamic and credible whole-process tracing capability.

Conversely, Ethereum, an innovative platform implemented as an open-source initiative, has significant deviations in terms of its objectives and underlying structure. The fundamental focus of Ethereum's architecture revolves around the development of DApps and smart contracts within the context of a public blockchain environment (Ehsan et al. 2022). Its ecosystem enables developers to conceptualize and construct applications that autonomously execute predetermined actions using smart contracts as a tool. The distinguishing feature of the platform is the provision of extensive support for a distinctive programming language called Solidity, which serves as the foundation for the development of these self-executing contracts (Peng et al. 2022a). Indicatively, a study outlines the process of creating a BC application for the purpose of tracking the origin and journey of table olives using the Ethereum network (Kechagias et al. 2023). The implementation of the BC application resulted in a notable enhancement in the producer's capacity to trace their products, including a decrease in the duration required for tasks, enhancement of the precision and dependability of data, optimization of the efficiency of the SC, and facilitation of the producer's adherence to international norms and standards. Similarly, an Ethereum-based framework is presented in (Yakubu et al. 2022) that is able to monitor all the interactions occurring among the many stakeholders within the rice SC. The suggested framework offers a secure, efficient, dependable, and efficacious method for monitoring and tracking the safety and quality of rice products, particularly during the process of product acquisition, and it exhibits superior performance compared to its predecessor in terms of cost-effectiveness, security, and scalability while also maintaining low computational overhead.

Overall, these two blockchain platforms highlight the multifaceted character of BC and its adaptable implementations, exhibiting distinct characteristics as shown in Table 3 (Valenta and Sandner 2017; Mohammed et al. 2021; Ucbas et al. 2023). From this comparison, Ethereum appears more suitable for public applications requiring high transparency, while Hyperledger Fabric provides greater control and efficiency for business-to-business collaborations.

In addition, in this study two distinct platforms were identified Openchain and Pure Proof-of-Stake Algorand. The coexistence of multiple platforms exemplifies the advancement of BC, providing adaptable instruments to transform many sectors, redefine mechanisms of trust, and reconfigure frameworks for transactions. Figure 11 quotes the quantity of the reviewed publications regarding the BC platform. Most of the reviewed articles used Ethereum-based (24) or Hyperledger fabric (24) solutions as Blockchain platform.

3.5 Ancillary Technologies

Within the dynamic landscape of FSCs, the integration of BC is complemented by a diverse range of auxiliary technologies that jointly enhance the revolutionary potential of this innovation (Tanveer et al. 2023). Table B2 in Appendix classifies the articles reviewed in this study pertaining to the ancillary technologies. Furthermore, Fig. 12 quantifies these articles by referring to the ancillary technologies utilized. In this subsection, these technologies are presented.

3.5.1 IoT

The integration of IoT with BC in the context of the FSC has emerged as a powerful synergy with the potential to revolutionize the way the industry operates. IoT refers to the network of interconnected devices and sensors that can collect, exchange, and transmit data over the internet (Valderas et al. 2023). When combined with BC, IoT enhances the traceability, transparency, and overall efficiency of the FSC, addressing critical challenges and improving various aspects of the industry (Pranto et al. 2021). In addition, with the real-time capture of the sensor

Table 3 Comparative characteristics of Ethereum and Hyperledger Fabric

Feature	Ethereum	Hyperledger Fabric
Network type	Public (Permissionless)	Private, Public, Consortium (Permissioned)
Scalability	Moderate	High
Performance	Low (proof of work (PoW))	High (Proof of Stake (PoS) and Byzantine Fault Tolerance (BFT) algorithms)
Currency	Ether – via smart contract	None, tokens and currency via chaincode
Smart contract support	Solidity	Chaincode (Go, Java, Node.js)
Primary use in FSC	Traceability & smart contracts	Confidentiality & enterprise use

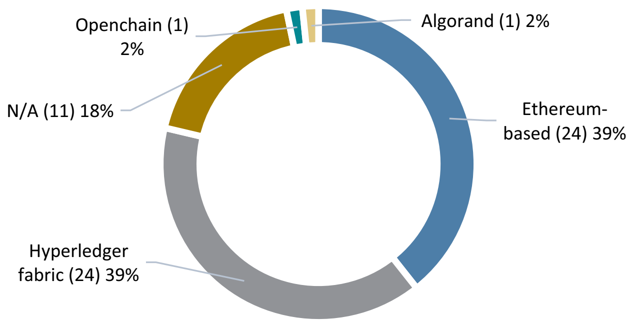


Fig. 11 Quantity of articles pertaining to BC platform

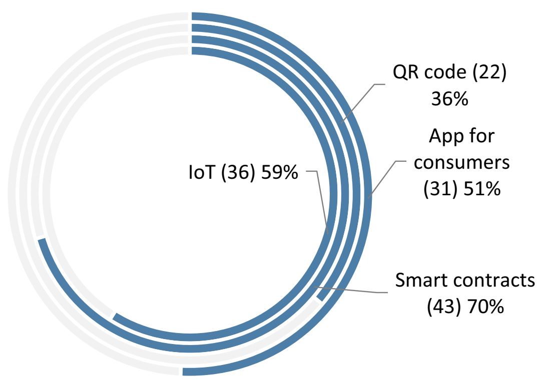


Fig. 12 Quantity of articles using ancillary technologies

data and the immutability that BC offers, the industry gains valuable insights into product conditions, transportation, and handling (Balamurugan et al. 2022). Furthermore, this integration allows for the secure exchange of data among participants, the automation of compliance processes, and the enhancement of informed decision-making capabilities. Many studies have identified that the convergence of IoT by enabling extensive data monitoring with blockchain technology, which enhances trust, offers a holistic solution with the potential to transform global food safety, authentication verification, and supply chain management (Fortino et al. 2018; Guo et al. 2021; Hasan et al. 2022; Valderas et al. 2023; Kumari et al. 2023).

The amalgamation of Radio Frequency Identification (RFID) technology within BC and IoT represents a significant progression in enhancing the efficiency, traceability, and transparency of the FSC. RFID enables the automatic identification and tracking of goods via the use of electromagnetic fields and by affixing RFID tags to products and containers, the entire journey of items through the SC is meticulously tracked, with the data seamlessly integrated into the BC (Tian 2016). In addition, the utilization of RFID technology facilitates the automation of inventory management processes, reduces waste by enabling real-time monitoring of product conditions, and enhances the effectiveness of compliance verification through the integration of BC (Gupta and Shankar 2023). In this review, RFID is highlighted among IoT devices as it has been referenced and used in several studies. In addition, 59% (36) of the studies utilize IoT into their solution (Fig. 12).

3.5.2 Smart Contracts

BC serves as the foundational framework for the secure and transparent storage and transmission of data, while smart contracts facilitate the automated implementation of predetermined rules and agreements inside the blockchain (Nofer et al. 2017). Collectively, these technologies provide novel opportunities for developing decentralized and streamlined systems across FSC. Digital contracts function inside the decentralized environment of the blockchain, executing predetermined activities upon the fulfillment of particular circumstances. Smart contracts, operating as coded protocols, provide trust and transparency by immutably recording their execution on the blockchain, minimizing the potential for disputes (Wang et al. 2019).

Scholars address the significance of food safety traceability in the context of agricultural food safety issues, and propose frameworks that utilize blockchain and smart contracts for monitoring and facilitating agricultural food trade (Wang et al. 2019, 2021; Valencia-Payan et al. 2022). Among the benefits reported is the security of the system, which exhibits attributes such as data accessibility, tamper-proofing, and resilience against man-in-the-middle attacks (Kechagias et al. 2023). In addition, the utilization of smart contracts provides automated and resilient procedures that result in enhanced and reliable traceability of food systems (Valencia-Payan et al. 2022). Moreover, smart contracts have the capability to automate payment procedures, by implementing predetermined conditions, such as the confirmation of successful delivery or the assessment of quality (Wang et al. 2021). This feature reduces payment delays and eliminates the need for intermediaries. In this SLR, 70% (43) of the studies utilize smart contracts into their solution (Fig. 12).

3.5.3 QR Code

The integration of QR code technology and blockchain has positive implications for increasing transparency and traceability throughout the FSC. QR codes, which are matrix barcodes capable of storing significant amounts of data, are utilized for the purpose of encoding information pertaining to a product's journey, origin, processing, and other relevant details. When integrated with blockchain technology, QR codes become gateways to accessing a wealth of immutable and verifiable data (Chatterjee and Singh 2023). QR codes may be scanned by stakeholders, such as consumers or retailers, using mobile devices, in order to obtain comprehensive information regarding the whole lifespan of the product (Jo et al. 2022). QR codes empower consumers to make informed choices by verifying authenticity, ethical practices, and quality assurances (Valderas et al. 2023). Additionally, it enables SC participants to instantly access real-time data about each product, fostering rapid responses to any discrepancies or issues (Dey et al. 2021). Thus, QR codes facilitate the utilization of BC in FSM by transforming a seemingly simple code into a powerful tool that enhances trust and traceability. In this SLR, 36% (22) of the studies utilize QR code into their solution (Fig. 12).

3.5.4 App for Consumers

The integration of blockchain technology into consumer-facing applications presents a unique opportunity to enhance transparency across the FSC (dos Santos et al. 2021). These apps allow consumers to scan QR codes or product identifiers with their mobile phones, to obtain extensive details on the product's whole supply chain, spanning from its origin at the farm to its final destination on the table. By accessing the BC's information, consumers can verify product authenticity, trace its origin, and access data related to quality standards and ethical practices (Keogh et al. 2020). Such applications create a channel for consumers to provide feedback and report issues, therefore playing a role in the continuous improvement of the integrity of the SC. By effectively incorporating blockchain technology and user-friendly applications, the customer experience is enhanced, transforming it from a passive act of consumption to an engaged involvement within a transparent FSC. In this SLR, 51% (31) of the studies utilize an app for consumers into their solution (Fig. 12).

3.6 Related Impact of Blockchain Adoption

The adoption of BC in FSCs has ushered in a new era of possibilities, reshaping the dynamics of an industry. Table B2 in Appendix classifies the articles reviewed in this study pertaining to the related impact of blockchain adoption. Furthermore, Fig. 13 quantifies these articles by the related impact referred. The related impact refers to technological, social, economic, environmental, and management aspects and provides a comprehensive lens through which to assess the sustainability dimensions of integrating BC into FSCs, as proposed from the newly introduced Common Agricultural Policy (2023–2027) framework. Sustainability, often framed within the pillars of social responsibility, economic viability, and environmental conservation (van der Aalst et al. 2023), represents

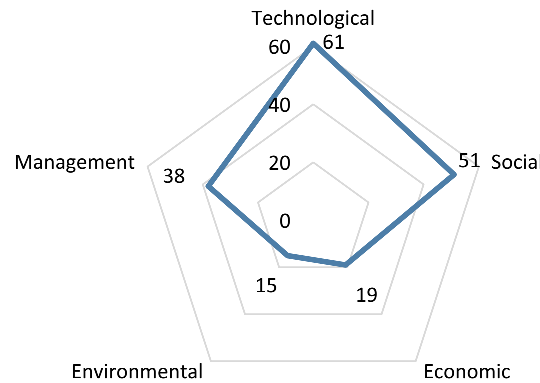


Fig. 13 Number of articles referring to the related impact

a critical paradigm in contemporary discourse and is enhanced with technological and management pillars as the related impacts. This multifaceted exploration underscores the pivotal role of blockchain in catalyzing a shift towards a more sustainable, transparent, and ethically grounded food ecosystem. In this subsection, the related impact of BC adoption is discussed, as identified in this research studied.

3.6.1 Technological

The use of BC in FSC has significant technological implications that change how the industry functions. Streamlined transparency is a significant operational advantage offered by BC (Dadi et al. 2021). This advantage stems from the immutable nature of the blockchain's ledger, which ensures a thorough and tamper-proof record of all transactions, movements, and transformations of products. The level of transparency observed encompasses the entire supply chain, spanning from producers to consumers, fostering real-time visibility into product origins, conditions, and handling practices (Iftekhar et al. 2021). In addition, the prevalent issue of information asymmetry within SCs is mitigated, hence facilitating well-informed decision-making, minimizing delays, and improving risk management (Yang et al. 2021). Moreover, the automation capabilities of BC have a substantial influence on the operational efficiency of the FSC. Smart contracts have the ability to eradicate the need for human interaction and intermediaries in a wide range of activities, including but not limited, to order fulfillment and payment settlements (Liu et al. 2022). This automation reduces administrative burdens, accelerates transactions, and enhances accuracy by removing the potential for human errors. Furthermore, the data-sharing capabilities of BC enable enhanced collaboration among actors in the supply chain, promoting a cohesive approach to tackling obstacles and improving operational efficiency (Evron et al. 2022; Sharma et al.

2023). In this SLR, all the studies refer to the operational impact of their solution (Fig. 13).

3.6.2 Social

The use of BC in FSC has significant societal ramifications that transcend its technological progress. At its essence, BC enables diverse participants, ranging from producers to consumers, to benefit from exceptional levels of transparency and accountability (Pandey et al. 2022). This transparency inspires consumer confidence, encouraging consumption decisions based on verifiable information regarding product origins, ethical practices, and quality (George et al. 2019). This has the ability to provide incentives for the adoption of sustainable and ethical practices within the food sector, while also effectively addressing concerns related to food fraud, mislabeling, and the presence of unsafe products (Krishna et al. 2021).

The literature mostly centers on the examination of the societal implications pertaining to the enhancement of food safety and authenticity, alongside the concurrent reduction of food fraud. In other words, the consumer's degree of trust is heightened due to the increased transparency of the supply chain (Tharatipyakul et al. 2022). BC contributions to society include reduction of food fraud, enhancement of food security, and provision of transparency to clients (Mangla et al. 2021). In light of this, a research implementing BC reported that their fraud incidents have plummeted by 80% as the fraud detection was increased from 70 to 95% with a substantial reduction in false positives of 10% (Ran et al. 2024). Moreover, it is stated that their consumer satisfaction index rose 12.5%, indicating a better experience, while customer complaints have dropped by 50%, indicating better service and responsiveness. It is also highlighted that the use of BC may contribute to ethical concerns, specifically in relation to fair trade and animal welfare (Adamashvili et al. 2021). This can be achieved through the implementation of inclusive development strategies that prioritize the accessibility of small producers to improved markets, as well as secure payment and financing options. In this SLR, 84% (51) of the studies refer to the social impact of their solution (Fig. 13).

3.6.3 Economic

Another factor pertaining to the influence of BC adoption is the economic aspect, particularly with regards to enhancing food safety and the financial implications associated with the application of BC systems. BC implementation serves as a means to address issues related to food fraud, while concurrently generating economic advantages by fostering increased customer confidence, mitigating legal risks, minimizing product recalls, and enhancing brand reputation (Katsikouli et al. 2021). More specifically, a study revealed a 25–30% reduction in claims expenses through automated verification with potential industry-wide cost savings of \$5–10 billion (Dhanekulla 2024). Similarly, another study revealed cost savings regarding inventory management by 20%, along with an 66.7% reduction in stockout incidents, and a decrease in administrative costs, with a decline of 25% of staff costs, 20% in travel and employee training costs, and 37.5 in legal fees (Ran et al. 2024). By creating a more transparent, accountable, and secure ecosystem, BC contributes to the prevention of economic losses caused by fraudulent activities (Krishna et al. 2021).

On the other hand, it has been asserted that the adoption of BC is a costly endeavor, necessitating the exploration of various strategies to address this issue (Niu et al. 2022). These strategies include augmenting the purchase price and enhancing e-tailing as a viable alternative. In addition, it is argued that the blockchain is incapable of facilitating cost-sharing contracts and revenue sharing in the context of SC coordination when implementing BC (Yang et al. 2021). It is stated that the implementation of BC has risen conflicts among suppliers, since it leads to an increase in procurement prices, due to significantly diversified transaction costs (Niu et al. 2022). However, there are others posit that the use of cryptographic proofs for validating the origin and handling state of food products has the potential to disrupt the food certification sector, by mitigating the expenses linked to audits and certifications (Tsolakis et al. 2021). This competitive advantage though needs adequate transformations of relative policy frameworks incorporating the positive impacts of BC on a regulatory level. In this SLR, 31% (19) of the studies refer to the economic impact of their solution (Fig. 13).

3.6.4 Environmental

The potential for driving beneficial environmental outcomes is substantial with the deployment of BC in the FSC. Through the enhancement of transparency and traceability, BC enables customers to make well-informed decisions regarding the items they purchase, therefore exhibiting a preference for those that adhere to environmental and ethical practices (Mihale-Wilson et al. 2022; Munir et al. 2022). This consumer-driven demand for transparency exerts pressure on producers to adopt environmentally friendly methods, reducing the ecological footprint of the food industry (Treiblmaier and Garaus 2023). Moreover, blockchain's ability to securely record and verify certifications related to organic, fair trade, and sustainable farming practices enhances the credibility of such claims, motivating more producers to adopt ecologically responsible practices. Furthermore, Blockchain's impact also extends to reducing food waste, a critical environmental concern, by providing real-time monitoring of temperature, humidity, and other conditions throughout the SC, BC helps prevent spoilage and deterioration of products (Dasaklis et al. 2022). The preservation of product integrity serves to minimize food waste resulting from inadequate storage or transit conditions, so promoting resource conservation and reducing the emissions associated with waste disposal (Patil et al. 2023). In this SLR, 25% (15) of the studies refer to the environmental or sustainability impact of their solution (Fig. 13).

3.6.5 Management

When identifying the impacts stemming from the adoption of BC in the FSC, the management dimension emerges as a crucial focal point. The integration of BC introduces transformative changes in managerial practices, offering a paradigm shift in how SC processes are orchestrated and overseen. Blockchain's decentralized and transparent nature streamlines managerial decision-making by providing real-time access to immutable and auditable data (Munir et al. 2022). This increased visibility into the SC, facilitates more informed strategic planning, allowing managers to proactively identify inefficiencies, optimize workflows, and mitigate risks (Marchese and Tomarchio 2022). The enhanced traceability afforded by Blockchain empowers managers to swiftly trace the origins of issues, whether related to food safety, quality, or logistics, enabling timely interventions. Moreover, BC's smart contract capabilities automate various aspects of contractual agreements, reducing the administrative workload on management and ensuring contractual compliance (Sharma et al. 2023). In a study, they witnessed a decrease in processing times by 40–70% by using BC (Dhanekulla 2024). While the integration of BC presents its own set of challenges for management, such as the need for expertise in blockchain technology and potential resistance to change, the overall impact is a more resilient and responsive management framework poised to navigate the complexities of the modern FSC.

4 Discussion

4.1 Challenges and Limitations

The integration of BC into the FSC holds transformative potential, yet it is not devoid of challenges and limitations that warrant consideration. While blockchain offers numerous advantages in enhancing transparency, traceability, and trust across the SC, certain gaps persist that necessitate careful implementation. From financial constraints and integration complexities to concerns regarding data accuracy and regulatory compliance, these challenges underscore the need for a comprehensive understanding of both the benefits and limitations of BC implementation. As many sectors endeavor to use the potential of blockchain technology to transform supply chain operations, it becomes crucial to conduct a balanced assessment of its limitations.

First and foremost, implementing blockchain requires initial investments in technology, training, and infrastructure (Niu et al. 2022). Small-scale producers and participants with limited resources might find it challenging to adopt the technology, potentially creating disparities in its utilization across the SC. In addition, the process of incorporating BC into pre-existing SC systems might present challenges and require a significant investment of time and resources. Compatibility issues arise from interoperability challenges with legacy systems, the need for data standards, and the requirement for interoperability across diverse blockchain platforms (Bellavista et al. 2021). Interoperability pertains to the capacity of different networks to communicate and exchange information with one another, in an effective and seamless way. Moreover, the absence of interoperability between hardware or software platforms in the agricultural sector results in technology users, such as farmers, being constrained to a user-agreement with a particular company, as stated by Glaros et al. (2023). The findings of the aforementioned study (Glaros et al. 2023) indicated that medium-scale farmers encountered significant difficulties, due to the absence of inter-platform interoperability. Additional time and effort are needed to execute recurring duties, such as inputting identical inventory information on various platforms, which can result in frustration and, in some cases, cessation of platform utilization. In light of this, the INTER-IoT methodology endeavors to furnish unobstructed interoperability, thereby facilitating vendors and developers to interact and interoperate while preserving their ability to compete by delivering a superior product and experience (Fortino et al. 2018). In addition, it facilitates the design and expeditious market entry of IoT devices, smart objects, and/or services for any enterprise, thereby establishing novel IoT interoperable ecosystems, considering the lack of universal IoT standards. Moreover, according to Kayikci et al. 2022a), it is stated that the establishment of universal guidelines for the acquisition and dissemination of data enhances the compatibility between stakeholders in the FSC and enhances the precision and availability of data. Nonetheless, accomplishing this objective poses a significant challenge, given the intricate global landscape within which the FSC operates.

Furthermore, the determination of what may and/or should be recorded on a blockchain, is the primary issue that must be addressed (Juan 2020). Determining which subset of quality management data should be shared and made available to supply chain participants, as well as between supply chains, is a difficult decision. In order to comprehend to which quality requirements a product conforms, certifications should be as transparent as feasible, given the problem of managing several standards (König et al. 2020). BC cannot address the issues arising from the presence of varied norms and standards for products within a shared SC. Nevertheless, in order to uphold elevated levels of food safety, it is imperative to build effective food control systems and harmonize standards at both the governmental and operational levels (Katsikouli et al. 2021). In light of this, some initiatives have been introduced from organizations, such as the Food and Agriculture Organization of the United Nations (FAO), or Global Food Safety Initiative (GFSI). The FAO's Codex Alimentarius is a compilation of standards, guidelines, and codes of conduct and its implementation plays a crucial role in guaranteeing the safety of food products and facilitating their international trade, while its aim is to provide science-based guidelines pertaining to all aspects concerning food safety and quality (FAO 2023). Correspondingly, GFSI, as a Coalition of Action, persists in uniting pivotal stakeholders, within the food sector, with the aim of collectively fostering ongoing enhancements in global food safety management systems. Their objective is to enhance and harmonize food safety systems, in order to adequately sustain the expanding worldwide population and establish markets capable of ensuring the safe delivery of food, irrespective of the consumer's geographical location (GFSI 2023).

Moreover, the reliability of data stored on a blockchain database surpasses that of a centralized database because of its immutability, preventing any kind of manipulation after the data has been entered into the system (Khan et al. 2023). Nevertheless, BC is unable of safeguarding against fraudulent endeavors that were instigated prior to the inclusion of data into the system. The lack of compliance between digital and physical goods is a significant vulnerability inside the system (Vasileiou et al. 2024b). This is one of the most formidable challenges that lies in the fact that the quality of data kept in a database is contingent upon the accuracy and reliability of the input and is frequently referred to as the "Garbage In – Garbage Out" problem (Powell et al. 2022). The incorporation of IoT devices and the implementation of automated transactions of smart contracts show potential as viable approaches to address this gap.

Last but not least, while BC enhances transparency and traceability within FSCs, a critical challenge that emerges is the balance between transparency and business confidentiality, particularly in competitive (cooperative yet competitive) environments. FSCs are inherently complex ecosystems involving multiple stakeholders, including suppliers, manufacturers, regulators, and retailers, each of whom may need to protect sensitive business information while still benefiting from BC's transparency. The implementation of BC presents a paradox: while it ensures traceability and transparency, it may inadvertently expose sensitive business data, raising concerns about competitive intelligence leaks and data privacy (Iftekhar et al. 2021). To address this issue, a promising approach known as the B-CONFIDENT Approach has been proposed by Agostinelli et al. (2024). This approach implements cryptographic mechanisms for data segmentation and access control, allowing stakeholders to share only essential information while protecting sensitive business data. It leverages cryptographic techniques to verify transactions and ensure compliance without exposing proprietary details, such as supplier pricing and sourcing strategies. Additionally, confidential transactions are facilitated through selective transparency mechanisms and differential privacy, enabling businesses to collaborate on a blockchain while safeguarding competitive advantages. Given that blockchain adoption in FSCs is often constrained by data confidentiality concerns, B-CONFIDENT offers a structured framework for selective information disclosure, ensuring that firms can maintain traceability without compromising strategic data – an especially crucial factor in SCs where multiple stakeholders operate in both collaborative and competitive roles.

Addressing these gaps and limitations requires a collaborative endeavor, involving stakeholders, technology refinement, regulatory adaptation, and a holistic approach to implementation. Notwithstanding the obstacles, the potential of blockchain technology to augment transparency, traceability, and accountability within the FSC remains substantial.

4.2 Integration of Blockchain and Artificial Intelligence

Building upon the challenges and limitations discussed in Sect. 4.1, which highlight the transformative potential of blockchain in the FSC alongside significant hurdles such as financial constraints, integration complexities, and data accuracy issues, an advanced integration of blockchain with Artificial Intelligence (AI) to further revolutionize the food industry is now explored. This study did not entail the use of AI in the SLR as it was not supported or suggested by the literature review articles. Nevertheless, there is an increasing inclination to utilize AI in addressing various issues, as it has been demonstrated to be a highly effective solution for many problems. While blockchain succors to transparency and traceability, its impact can be significantly amplified when combined with AI, which excels at analyzing data and prediction issues. This amalgamation can effectively tackle certain existing obstacles, such as ensuring data accuracy and system compatibility, while providing stronger solutions for food safety and fraud prevention. In the subsections that are to follow, (a) the emerging trends and transformative technologies shaping the food industry are discussed; (b) the crucial role of AI in enhancing food safety and fraud detection is assessed; (c) the integration of blockchain and AI for superior FSC management is examined; and (d) a conceptual architecture that underscores the potential of this integration to address current challenges and achieve new efficiencies is proposed.

4.2.1 Emerging Trends and Transformative Technologies

The transition from Industry 4.0 to Industry 5.0 signifies a substantial evolution in the integration of advanced technologies within the food industry (Hassoun et al. 2024; Rijwani et al. 2024). Industry 4.0, characterized by the extensive adoption of IoT, big data, AI, and blockchain, has significantly enhanced the efficiency and transparency of supply chain operations. For instance, IoT devices generate vast amounts of data, which, when analyzed, can optimize agricultural processes, monitor food quality, and improve traceability (Misra et al. 2022). This technological foundation has set the stage for advancements such as Food Traceability 4.0 (Hassoun et al. 2023) and Agri-Food 4.0 (Dadi et al. 2021), focusing on ensuring food authenticity, safety, and quality through digital innovation.

Alongside, BC has transcended its financial origins to find extensive application across various industries, including agriculture. Its decentralized capability BC makes it a promising tool in enhancing transparency and traceability within agriculture, as highlighted in this study. Integrating blockchain into systems like Food Traceability 4.0 expands on the foundational technologies of Industry 4.0, utilizing advanced digital solutions to track and verify food products throughout supply chains (Hassoun et al. 2024). Technologies like IoT, AI, and big data analytics also play pivotal roles in this domain, ensuring clear and unchangeable records that build trust among consumers and stakeholders. However, the widespread adoption of these technologies faces challenges such as high costs and complex technology requirements, highlighting the need for further research to overcome these obstacles and fully realize the benefits of digital innovations in food safety and sustainability (Morella et al. 2021).

Similarly, Agri-Food 4.0 aims to transform agricultural supply chains by integrating IoT, AI, robotics, and blockchain to improve food safety, quality, and traceability. This shift emphasizes creating smart and sustainable supply chain systems that can adapt to the evolving demands of global food production and distribution, as evidenced by recent reviews of Agri-Food 4.0 innovations (Dadi et al. 2021). The forthcoming era of Industry 5.0 envisions a deeper collaboration between humans and machines, aiming to enhance efficiency and sustainability even further. This next industrial revolution utilizes technologies such as edge computing, robotics, big data analysis, and 6G, encouraging innovations that promise to reshape food production and supply chains (Rijwani et al. 2024). As digital transformation continues, these advancements will play a pivotal role in ensuring a more secure and sustainable food future (Konfo et al. 2023).

4.2.2 The Role of AI in Food Safety and Food Fraud Detection

Artificial intelligence plays a crucial role in enhancing food safety and detecting food fraud, as extensively documented in the literature (Buyuktepe et al. 2023). To begin with, the food processing and handling industry, a pivotal sector globally, drives extensive employment within manufacturing. Integrating AI-based systems promises to streamline food production and delivery, enhancing operational efficiency, minimizing human errors, and optimizing resource utilization through predictive analytics for sales and production optimization (Kumar et al. 2021).

AI adoption in FSCs offers solutions to critical challenges, such as food safety, quality control, and waste reduction by enhancing transparency and traceability (Kumari et al. 2023). Key critical success factors encompass technology readiness, security, privacy, customer satisfaction, perceived benefits, demand volatility, regulatory compliance, competitor pressure, and information sharing among partners (Dora et al. 2022). These insights are crucial for AI technology providers, supply chain specialists, and policymakers to develop effective strategies supporting AI adoption in FSC and addressing ethical considerations (Gbashi and Njobeh 2024).

The AI Institute for Next Generation Food Systems (AIFS) aims to advance AI technologies tailored to diverse challenges across the FSC, promoting innovation in food production, distribution, and nutrition to enhance efficiency, quality, and sustainability (Tagkopoulos et al. 2022). Vinothkanna et al. (2024) underscored the critical role of advanced detection technologies and chemometrics in combating food fraud within modern SCs. Their review highlights the adoption of AI-based techniques as integral to advancing detection systems, emphasizing the need for further research to optimize efficacy, simplicity, cost-effectiveness, and environmental sustainability in fraud detection methodologies.

The global FSCs face increasing complexities and scalability challenges, exacerbated by shifts in environmental, demographic, and economic factors, which heighten the risks of food fraud and safety hazards. To address these threats, the integration of eXplainable Artificial Intelligence (XAI) techniques such as LIME, SHAP, and WIT emerges as a pivotal strategy (Buyuktepe et al. 2023). These XAI methods enhance transparency and interpretability in predicting food fraud risks, utilizing deep learning models trained on diverse datasets. It is worth mentioning that Deep Learning (DL) is proving effective in analyzing large datasets across diverse fields, including food science and engineering (Shukla et al. 2023). DL techniques like Convolutional Neural Networks (CNNs) and AI offer innovative solutions for food safety inspection and supply chain management, showcasing DL's potential to revolutionize these areas beyond traditional methods.

Additionally, recent developments in Bayesian Network (BN) and Failure Modes and Effects Analysis (FMEA) present promising avenues for assessing and mitigating food fraud vulnerabilities in specific supply chains, such as spices entering Europe (Bouzembrak et al. 2024). By analyzing data from reported fraud cases, these models achieve high prediction accuracies, pinpointing key variables like product type, intervention site, and country of origin that influence vulnerability levels. This precision enables targeted monitoring and detection efforts, empowering stakeholders in the food industry and regulatory bodies to proactively safeguard food integrity and public health.

Moreover, Wang et al. (2013), highlighted significant advancements in food safety management and supply chain optimization through the integration of AI and advanced analytics. Initially, the Hazard Analysis and Critical Control Points (HACCP) system is mentioned for its proactive approach in ensuring food safety across the SC. This system is complemented by the introduction of the Supply-chain Pedigree Interactive Dynamic Explore (SPIDER), a secure global platform utilizing AI techniques such as Case-based Reasoning, Rule-based Reasoning, Fuzzy logical, and Neural Network. SPIDER enhances data analysis, verification, and investigation capabilities, facilitating robust implementation of HACCP principles within the food industry.

Furthermore, the implementation of Quality Sustainability Decision Support Systems (QSDSS) in industries like the red wine sector exemplifies the practical application of AI to enhance logistics planning and maintain food quality and safety (Ting et al. 2014). By utilizing association rule mining and Dempster-Shafer theory, QSDSS optimizes logistics strategies, effectively mitigating quality risks inherent in complex global supply chains. This case study underscores the pivotal role of AI-driven decision support systems in strengthening quality assurance practices and ensuring consistent food safety standards.

Additionally, the integration of open data and AI is explored as a transformative approach to enhance food safety by predicting and mitigating risks associated with unsafe goods in real-time (Makridis et al. 2023). Through the deployment of deep learning, natural language processing, time-series forecasting, and reinforcement learning techniques, the study proposes innovative methods to monitor and forecast food recalls.

In conclusion, the application of AI-driven technologies represents the transformative potential of AI and advanced analytics in revolutionizing food safety management, logistics planning, and risk mitigation within the global food SC. As advancements continue, further integration and refinement of AI methodologies promise to fortify resilience against evolving threats in food safety and fraud mitigation.

4.2.3 Integration of Blockchain and AI for Enhanced Food Supply Chain Management

The integration of blockchain technology and AI presents a transformative opportunity for FSCs, aiming to enhance security, efficiency, and transparency. Recent studies reveal that combining these technologies can significantly enhance various aspects of supply chain management, particularly in sectors like food safety, manufacturing, and agriculture.

The study of Chen et al. (2023) demonstrates how integrating XAI and blockchain technology in smart agriculture can substantially improve food safety by enabling precise contamination detection and efficient supply chain management. The unchangeable and transparent ledger provided by blockchain technology ensures accurate tracking of perishable food items, facilitating the rapid identification and removal of contaminated products from the market (Thume et al. 2022). This integration not only enhances food safety but also increases efficiency, transparency, and sustainability within the food chain, benefiting farmers, consumers, and the global community.

Another study highlights the potential of blockchain technology to secure AI-assisted manufacturing systems, addressing the special requirements of manufacturing blockchains compared to generic ones (Patel et al. 2024). This framework enhances data security, collaboration, and trust among participants, which are critical for maintaining the integrity of the SC. By utilizing blockchain, manufacturers can secure supply chains against counterfeit products and promote ethical consumerism, which is crucial for maintaining consumer trust and ensuring product quality.

Additionally, integrating AI into blockchain technology can further enhance its security, efficiency, and reliability, addressing challenges such as consensus, scalability, and interoperability (Ressi et al. 2024). This integration fosters innovation and improves data privacy and smart contract functionality, which are essential for a robust and transparent FSC. Moreover, the application of ML and blockchain in IoT environments represents a highly promising approach by improving Quality of Service (QoS) parameters, such as delay, throughput, packet delivery ratio, and packet drop. According to CheSuh et al. (2024), advanced ML models achieve notable enhancements in these QoS parameters, ensuring uninterrupted connectivity and high-quality access to IoT devices within FSCs. This synergy is crucial for maintaining the efficiency and reliability of real-time monitoring systems, which are essential for food safety and quality assurance.

In summary, the integration of AI and blockchain technologies in FSC management systems underscores the importance of adopting innovative solutions to address contemporary challenges. By combining the strengths of both technologies, stakeholders can achieve enhanced transparency, security, and efficiency, ultimately leading to a more reliable and sustainable FSC. This integration not only meets the growing demands for food safety and quality but also supports the development of smart agriculture and ethical manufacturing practices, driving the industry towards a more secure and efficient digital future.

4.2.4 Conceptual Architecture for Future Work

To illustrate the potential of integrating blockchain and AI in FSC management, a conceptual architecture that outlines the key components and their interactions is proposed (Fig. 14).

The proposed architecture consists of several interconnected layers designed to enhance transparency, efficiency, and safety across the FSC. By integrating these layers, the conceptual architecture aims to establish a robust framework for managing the FSC effectively. It utilizes blockchain's security and transparency features alongside AI's analytical capabilities to mitigate risks, optimize processes, and ensure the safety and quality of food products from farm to table. This architecture not only enhances operational efficiency but also supports stakeholders in making informed decisions based on reliable, real-time data and insights. These layers are explained as follows:

4.2.4.1 Data Collection Layer At the foundation of the proposed conceptual architecture lies the Data Collection Layer, where IoT Sensors and Devices play a pivotal role in capturing detailed data essential for the digital product passport. These devices continuously monitor environmental conditions and capture timestamps, providing real-time insights into the journey of each product through the SC. Complementing this automated data collection, Manual Data Entry incorporates certifications, inspection results, and other manually gathered information into the digital product passport. This dual approach ensures a comprehensive and accurate representation of each product's history and compliance status.

4.2.4.2 Blockchain Layer Securing the integrity and transparency of data across the supply chain, the Blockchain Layer employs a Distributed Ledger to store digital product passports. This blockchain-based solution guarantees immutability, preventing unauthorized alterations or tampering throughout the product's lifecycle. Smart Contracts embedded within the blockchain automate updates to the digital product passport based on AI-driven insights. These contracts also trigger predefined actions, ensuring swift responses to detected issues such as safety concerns

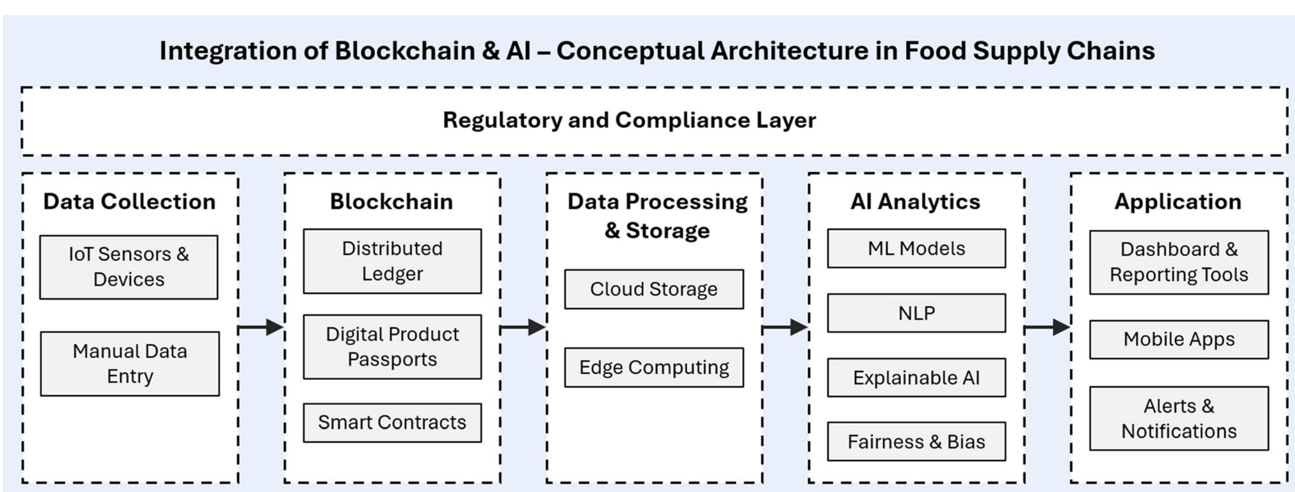


Fig. 14 Integration of Blockchain & AI – Conceptual Architecture in Food Supply Chains

or regulatory non-compliance, thereby bolstering operational efficiency and trust among stakeholders.

4.2.4.3 Data processing and Storage Layer Handling the vast volumes of data associated with digital product passports, the Data Processing and Storage Layer utilizes Cloud Storage for secure and scalable data management. This layer utilizes Edge Computing to process data at the edge of the network, facilitating real-time updates to the digital passport. By decentralizing processing tasks closer to where data is generated, Edge Computing enhances responsiveness and ensures timely updates to stakeholders throughout the supply chain.

4.2.4.4 AI analytics Layer Driving proactive decision-making and risk mitigation strategies, the AI Analytics Layer employs ML Models to analyze data extracted from digital product passports. These models predict potential safety issues and detect fraudulent activities, updating the passport with actionable insights and interventions taken. This layer is further enriched by Natural Language Processing (NLP) capabilities by extracting and updating relevant textual information, ensuring a comprehensive and dynamic record of each product's journey and compliance status. Moreover, the integration of XAI techniques within the AI Analytics Layer ensures transparency in decision-making processes (Minh et al. 2022). XAI methods provide stakeholders with insights into how AI models arrive at specific conclusions, enhancing trust and facilitating compliance with regulatory requirements for transparency in automated decision systems. Finally, addressing bias (Corliss 2024) and fairness (Jui and Rivas 2024) in AI algorithms within the AI Analytics Layer is crucial for equitable decision-making across diverse populations.

4.2.4.5 Application Layer Facilitating seamless access and interaction with digital product passports, the Application Layer provides intuitive Dashboard and Reporting Tools for stakeholders. These tools offer comprehensive views of product histories, safety records, and compliance statuses, empowering users with actionable insights for informed decision-making. Mobile Applications extend accessibility, allowing supply chain participants and consumers to access digital passports on-the-go, fostering transparency and consumer confidence. Automated Alerts and Notifications within the passport document critical events and updates, ensuring stakeholders remain informed in real-time.

4.2.4.6 Regulatory and Compliance Layer Ensuring adherence to regulatory standards and certification requirements, the Regulatory and Compliance Layer integrates a dedicated Regulatory Compliance Module within the digital product passport. This module consolidates all necessary compliance records, certifications, and audit trails, facilitating seamless regulatory audits and compliance verification. Utilizing the immutable nature of blockchain records, audit trails within the passport provide verifiable proof of adherence to regulatory guidelines, enhancing trust and accountability across the entire FSC.

5 Conclusions

In summary, the integration of blockchain technology within food supply chains represents a significant intersection between industry and innovation, as well as an opportunity for academia to engage in interdisciplinary investigations. The synergistic assimilation of blockchain's attributes serves as a beacon for addressing long-standing industry challenges, promoting transparency, ensuring authenticity, and enhancing security. Through a systematic literature review, this research has explored and synthesized the multifaceted dimensions of blockchain implementation in FSC management. The analysis spanned six thematic areas, each shedding light on distinct facets of blockchain's role and impact, guided by distinct criteria. From the 2097 documents found, 122 full-text articles were assessed, and 61 were included and classified in this study based on the criteria.

Under "General Information", this review meticulously documented the evolution of blockchain in FSCs, offering insights into the increasing recognition of its potential as evidenced by a growing body of literature across diverse publishing sources, industries, and document types. Within the "FSC Application" thematic area, blockchain's versatility was showcased, transcending international borders and spanning various sectors. The criteria of industry and country delineated the diverse contexts in which blockchain solutions are deployed, emphasizing their adaptability and relevance in addressing FSC challenges globally. In addition, the exploration of "Factors of BC Adoption" thematic area unveiled the multifarious criteria underpinning blockchain integration, including transparency and traceability, food safety and quality, security and trust, and the demand for consumer authenticity. A closer examination of the "Blockchain Platform" criterion delved into the underlying technical infrastructures shaping blockchain implementations. Furthermore, in the "Ancillary Technologies" thematic area, the synergy between blockchain and ancillary technologies, such as IoT, smart contracts, QR codes, RFID, and consumer apps, was evident. These criteria elucidated how these complementary technologies amplify blockchain's transformative potential, reinforcing its influence on the FSC landscape. Last but not least, the analysis of the "Related Impact of BC Adoption" thematic foci illuminated a spectrum of advantages, encompassing technological streamlining, enhancing social trust, economic benefits, reduction of environmental footprints, and ramifications to management. These criteria underscored blockchain's capacity to foster transparency, resilience, and sustainability within FSCs.

In conclusion, this SLR has contributed to the burgeoning discourse on BC's transformative influence on FSC management. The findings underscore the pivotal role of BC in addressing the intricate challenges of FSCs, thereby advancing food safety, traceability, and the overall integrity of the global food supply. Moreover, the integration of IoT devices, sensors, and other data sources enables comprehensive monitoring of a product's journey, spanning from its starting point through its ultimate consumption by end users. This facilitates prompt identification of the origin of infection or contamination, hence enabling focused recalls and mitigating the consequences for customers. However, the process of integrating BC into the FSC is a complex endeavor that requires careful coordination, technological expertise, and ongoing adjustment to a rapidly changing environment. It is clear that while blockchain cannot single-handedly eradicate every challenge, it serves as a cornerstone for building up positive change. This transformation is not confined to operational optimization; it extends to profound economic, social, and environmental implications, catalyzing a shift towards a more equitable, transparent, and resilient food ecosystem. To maximize blockchain's potential, ongoing research, industry collaboration, and regulatory engagement are imperative.

Furthermore, the successful deployment of BC necessitates a certain degree of digital literacy among every stakeholder engaged in the supply chain, encompassing both producers and consumers. Understanding how BC operates, the implications of decentralized systems, and how to interact with blockchain-based platforms is essential. The lack of digital literacy could lead to misconceptions, mistrust, and errors in utilizing blockchain systems effectively. To tackle this challenge, it is imperative to implement training and educational programs that provide all individuals with the necessary skills and knowledge to effectively and comfortably interact with solutions provided by BC. What is more, in FSCs, companies often operate within established processes and practices, some of which have remained unchanged for decades. Introducing BC disrupts these norms, necessitating shifts in behavior, workflows, and mindsets. Resistance to change can stem from concerns about job displacement, the complexity of adapting to new technologies, and the fear of the unknown. This issue can impede the adoption of BC and limit its potential impact. To address such an issue requires the utilization of efficient change management tactics, that encompass transparent communication, collaborative efforts, and active engagement of relevant stakeholders throughout the design and execution phases.

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