Lisbon School of Economics & Management
Universidade de Lisboa

MASTER

INNOVATION AND RESEARCH FOR SUSTAINABILITY

MASTER´S FINAL WORK

DISSERTATION

LEVERAGING BLOCKCHAIN TECHNOLOGY AS A TOOL IN THE FOOD SUPPLY CHAIN TO COMBAT FOOD FRAUD: A SYSTEMATIC LITERATURE REVIEW

DIEM PHUONG TRAN NGO

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SUPERVISION:

WINNIE NG PICOTO

JUNE 2025

"Neither life nor innovation

are at all simple or linear"

-Tornatzky et al., 1990, p. 30

GLOSSARY

AI - Artificial Intelligence.

BC – Blockchain.

BCT - Blockchain technology.

FS - Food supply.

FSC - Food Supply Chain.

IoT - Internet of Things.

ML - Machine Learning.

NFC – Near Field Communication.

PDO – Protected Designations of Origins.

PGI – Protected Geographical Indications.

PUF – Physical Unclonable Function.

QR – Quick Response.

RQ – Research Question.

SC – Supply Chain.

SM - Smart Contracts.

SLR – Systematic Literature Review.

SME – Small and Medium Enterprises.

TOE - Technological-Organizational-Environmental.

WoS – Web of Science.

WSN – Wireless sensor network.

ABSTRACT

This dissertation aims to provide a state-of-the-art overview of blockchain’s ability to enhance traceability and transparency. It focuses on combating food fraud and identifying the key barriers to its widespread adoption in the food supply chain. The review applies a qualitative approach, utilizing a systematic literature review methodology to address two research questions: “How can blockchain technology enhance transparency and traceability in the food supply chain to combat food fraud?” and “What are the key barriers to adopting blockchain technology in the food supply chain?". This SLR collected data from Web of Science and Scopus, yielding 96 publications based on keywords such as "blockchain," "distributed ledger," "food fraud," "food supply chain," "transparency," and "traceability." Following PRISMA 2020 guidelines and predefined inclusion and exclusion criteria, along with minimum quality assessment criteria, a final sample of 36 publications was included in the review. Thematic analysis and the Technological-Organizational-Environmental framework were employed to synthesize the data. The findings revealed that blockchain technology, as a decentralized, immutable, and distributed ledger system, provides a better traceability system and enhances transparency in the food supply chain compared to traditional systems with centralized databases. They are often vulnerable to single points of failure and information asymmetry due to centralized databases. Additionally, the review identified 14 barriers to its widespread adoption, spanning technological, organizational, and environmental dimensions.

Overall, blockchain technology can significantly increase supply chain transparency, mitigating food fraud by facilitating better information flow among stakeholders. It enables a more robust traceability system that goes beyond the current EU Reg. 178/2002 "one step forward, one step backward" approach. As this review focuses on the state of the art of blockchain technology in the food supply chain to combat food fraud, to the best of the author's knowledge, it is one of the few studies that examine blockchain’s advancements in this domain. The insights from this dissertation apply to other industries and can be harnessed by researchers and industry stakeholders to develop a more efficient and resilient food supply chain, as well as inform and elevate purchase decisions among consumers.

KEYWORDS: Blockchain; Distributed Ledger; Food Fraud; Food Supply Chain; Transparency; Traceability.

JEL CODES: D83, k19, L15, L66, O33

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Lisbon, Portugal, April 2025.

Diem Ngo

1. Introduction

Globalization and the growing complexity of the food supply chain have magnified food fraud, presenting substantial risks to public health and economic stability (Maritano et al., 2024). It is estimated that 600 million people suffer from foodborne illnesses annually, resulting in 420,000 deaths (Adamashvili et al., 2021). High-profile scandals, including the 2008 melamine contamination in China and the 2013 horse meat scandal in Europe, exposed vulnerabilities in traditional traceability systems (Chandan et al., 2023; Hassoun et al., 2023). Similarly, the 2011 food theft scandal in India further exposed vulnerabilities in the food supply chain, in which bad actors exploit gaps in existing systems with the intention of financial gain. This reinforces the limitation of traditional traceability systems and the growing need for more robust systems to ensure food integrity and safety. Noteworthy, fraudulent practices not only compromise product integrity but also erode consumer trust and create an unfair market dynamic (Guruswamy et al., 2022; Katsikouli et al., 2021).

Traditional traceability systems relying on centralized databases are vulnerable to manipulation, data silos, and single points of failure (Mao et al., 2018; Zheng et al., 2023). Information asymmetry further stimulates fraud, challenging the detection and prevention of opportunistic behavior (Zarba et al., 2024). Blockchain technology, on the other hand, provides a decentralized, immutable, and distributed system that fortifies transparency and traceability (Mercuri et al., 2021; Treiblmaier & Garaus, 2022). It enables real-time verification of product information, elevate accountability among supply chain actors, and cultivates consumer trust (Panigrahi et al., 2024; Vitaskos et al., 2024). In spite of blockchain's potential, its application in the FSC is facing barriers such as (i) technological (scalability, interoperability, data integrity, integration, technological immaturity, and cost), (ii) organizational (implementation and maintenance costs, technical skills, resistance to change, and trust issues), and (iii) environmental (regulatory frameworks, infrastructure, stakeholder trust, and consumers).

1.1. Background and Context

Today's modern food supply chain is a complex network involving numerous stakeholders who depend on effective traceability systems to ensure product authenticity and quality (Chiaraluce et al., 2024). Increasing digitization and consumer demand for transparency amplify the need for technological interventions (Garzón et al., 2024). Globalization has accelerated the risk associated with food fraud due to challenges in detection, enforcement, and regulatory compliance (Everstine et al., 2024). Blockchain technology provides a fruitful tool by enhancing transparency and traceability, ergo mitigating fraudulent practices in the FSC (Duan et al., 2024; Vitaskos et al., 2024). Traditional tracking systems often rely on manual paper records and isolated databases, making them vulnerable to manipulation and inefficiencies (Mercuri et al., 2021; Ellahi et al., 2024). To address these challenges, two research questions have been developed to understand blockchain's ability to enhance traceability and transparency in the FSC, focusing on combating food fraud and identifying the key barriers to its adoption in the FSC. The research questions and their objectives are presented in Table I.

Table I - Research Questions and Objectives.

	Research Question	**Research Objective**
RQ1	How can blockchain technology enhance traceability and transparency in the food supply chain to combat food fraud?	To examine the mechanisms through which BCT enhances traceability and transparency in FSC, and to identify specific BC characteristics that contribute to combat food fraud.
RQ2	What are the key barriers to adopt blockchain technology in the food supply chain?	To identify and categorize barriers and challenges associated with BC adoption in the FSC.

1.2. Dissertation Structure

In addition to this introduction chapter, this dissertation is structured into five main chapters. The second chapter presents a literature review, the third chapter introduces the methodology, and the fourth chapter presents the result addressing RQ1 and RQ2, along with a discussion section. The fifth chapter presents the conclusion, research limitations, and recommendations for future research. The structure of this dissertation is illustrated in Figure 1.

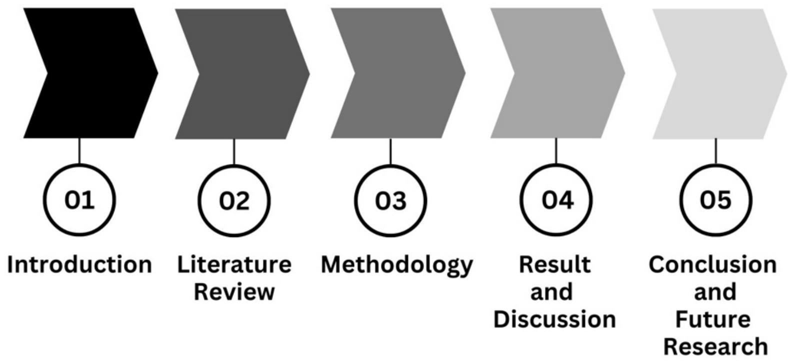

Figure 1 - The structure of this dissertation.

Source: Figure by the author.

2. Literature Review

This chapter reviews the relevant literature to establish the foundation for the research objectives. It first introduces food fraud and its impact on the food supply chain. Then, it introduces traditional approaches to combating food fraud, followed by blockchain technology and its applications in the food supply chain.

2.1. Food Fraud and Its Impact on the Food Supply Chain

The food supply chain (FSC) involves multiple stages and numerous stakeholders, ranging from production to final consumption. These include farmers, processors, distributors, retailers, consumers, and regulatory bodies overseeing food safety and standards (Garzón et al., 2024), as illustrated in Figure 2 by Tang et al. (2024).

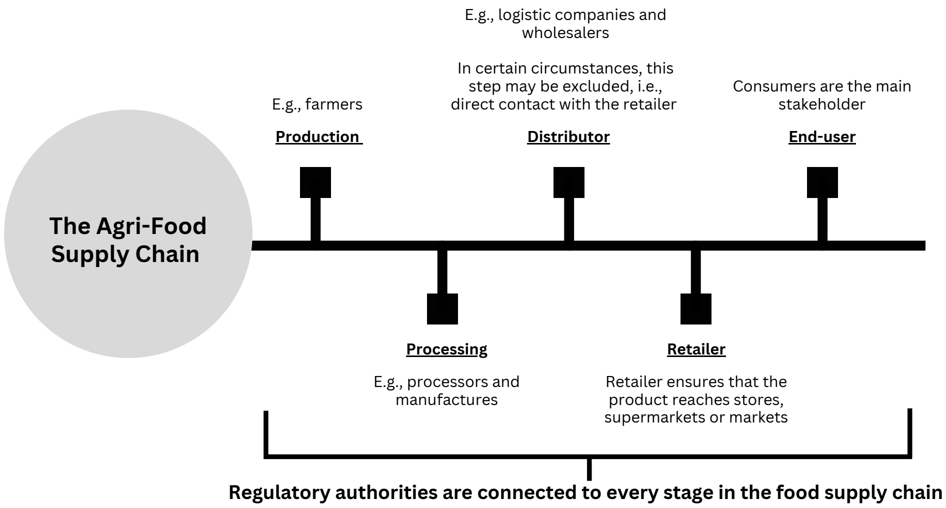

Figure 2 - Stakeholders in The Agri-Food Supply Chain

Source: Figure by the author based on Tang et al. (2024).

The global nature of the FSC and the absence of standardized traceability mechanisms create opportunities for food fraud. Food fraud includes mislabelling, adulteration, and counterfeiting, which jeopardize not only public health and economic stability but also trust among stakeholders (Jellason et al., 2024). Food fraud encompasses deliberately misrepresenting a product's identity or composition with the intention of financial gain, often through substitution, addition, or tampering (Everstine et al., 2024). The economic consequences of food fraud for the global food industry are estimated to be \$30-\$40 billion annually (Maritano et al., 2024). These losses stem from direct financial impacts on consumers through fraudulent practices, damage to legitimate producers' reputations, and increased compliance and fraud prevention expenses (Treiblmaier & Garaus, 2022). Notably, Tang et al. (2024) highlight that food fraud affects approximately 10 percent of all commercially sold food products worldwide.

The Sankey diagram in Figure 3 is a multilevel illustration of food fraud and adulteration events in January 2025 by the European Commission (Union, 2025). From left to right, it presents the countries where the events occurred, the food products affected, and what types of fraud were committed.

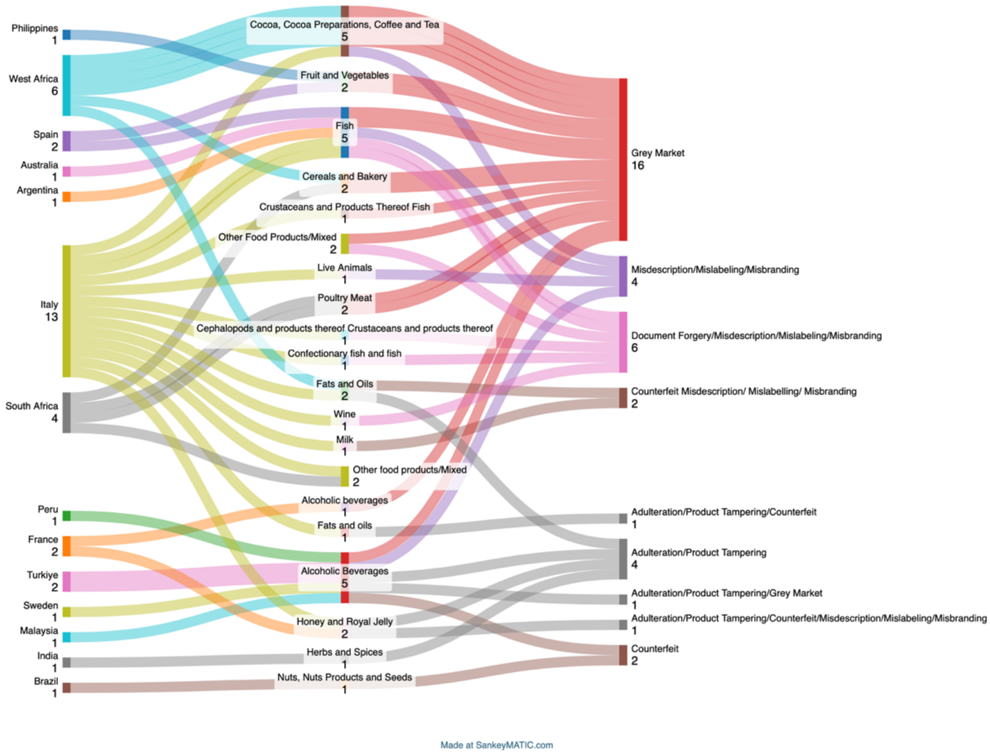

Figure 3 - Sankey Diagram of Food Fraud and Adulteration Events.

Source: Figure by the author based on Union (2025).

As seen in Figure 3, the countries involved span from various corners of the world, demonstrating that food fraud is a global concern. Additionally, food fraud includes mislabelling and false documentation, in which mislabelling involves deliberately misrepresenting a product's provenance, ingredients, or nutritional profile. Product substitution, where higher-quality ingredients are replaced with lower-quality ones without the consumer's knowledge, is a form of fraudulent practice (Bager et al., 2022). For instance, in seafood industries, practices such as species substitution are commonly reported (Patro et al., 2022). Similar issues have been documented in the certification and labeling of organic products, halal foods, and items with geographical indications (Mališić et al., 2023).

Adulteration is another type of food fraud, in which inferior or unauthorized substances are added to food products to increase volume or improve perceived quality. This practice is often seen in sectors such as olive oil, honey, and dairy, in which products are commonly diluted with cheaper alternatives (Khanna et al., 2022; Vitaskos et al., 2024). Counterfeiting, involving the false marketing of products under established brand names and fraudulent branding which misleads consumers into purchasing substandard or potentially harmful goods, is notably prevalent in high-value markets such as wine, extra virgin olive oil, and infant formula (Adamashvili et al., 2021; Goyal et al., 2023). Not to mention intentional contamination, in which hazardous substances are added to food products for financial gain. This is exemplified by the 2008 melamine contamination of dairy products in China and the 2013 horse meat scandal in Europe (Mohammed et al., 2023). In Table II, Maritano et al. (2024) describe the different types of food fraud.

Table II - Different Types of Food Fraud.

Type	Description
Adulterate	A component of a legitim finished product is fraudulent.
Counterfeit	All aspect of a fraudulent product and package are fully replicated.
Diversion	The sale of distribution of a legitimate product outside the intended markets.
Over-run	A legitimate product is made in excess off a legitimately procured.
Simulation	All illegitimate products are designed to look like but not exactly copy a legitimate product.
Tamper	A legitimate product and package are used in a fraudulent way.
Theft	A legitimate product is stolen and passed off as legitimately procured.

Source: Table by Maritano et al. (2024)

2.2. Traditional Approaches to Combating Food Fraud

The traditional food supply chain, which has provided consumers with a vast array of food products for centuries, often relies on paper-based records, with only a small portion of data digitized and searchable (Pearson et al., 2019). Due to these paper-based records, information often exists in separate silos (Chiaraluce et al., 2024). This centralization of databases cultivates information asymmetry, which limits data accessibility and creates opportunities for bad actors to exploit vulnerabilities in the FSC systems, introducing fraudulent products into legitimate SC. Bad actors often operate covertly and in parallel with legitimate SC, embedding themselves within authorized and certified organizations, making detection even further complicated (Brooks et al., 2021).

Existing efforts to combat food fraud include collaborative networks and scientific authentication methods, such as DNA testing and regulatory frameworks like the EU Agri-food Fraud Network (Duan et al., 2024). Additionally, traditional measures rely on manual paper-based documentation and centralized control, making them highly vulnerable to fraudulent practices (Maritano et al., 2024;Melissari et al., 2024;Panigrahi et al., 2024). Traditional traceability systems, including barcodes, RFID, and QR codes, improve automation but do not verify data authenticity (Zheng et al., 2023). Advanced authentication methods such as DNA barcoding, hyperspectral imaging, and spectroscopic analysis improve fraud detection but are still vulnerable to manipulation (Alkhudary et al., 2022;Hassoun et al., 2023).

Voluntary sustainability standards such as Fair Trade, Rainforest Alliance, and digital authentication tools like barcode-based labeling and smart packaging provide additional transparency (Bager et al., 2022;Jiménez-Carvelo et al., 2022). Regulatory mandates, such as the EU Reg. 178/2022 "one step forward, one step backward" approach, aim to connect all actors in SC by ensuring that each actor knows their suppliers and the next recipient of their products. However, this approach is ineffective in complex SCs where food products go through multiple steps and branches, like multi-ingredient products which include elements from different sources in various countries (Pearson et al., 2019).

Verny and Guan (2022) note that the currently deployed food traceability system is neither integrated nor linked among all participants in the SC. This disconnection generates information asymmetry between SC actors, reinforcing limited SC transparency. Figure 4 by Cammarano et al. (2023) illustrates the ”one step forward, one step backward” approach between actors in the FSC. Demonstrating that actors in the FSC manage their relationships with the closest actors to their left (upstream) and the actors to their right (downstream). The documentation signing step is manual and often creates issues of authenticity and incorrect documentation, consequently leading to longer processing times for monitoring (Cammarano et al., 2023).

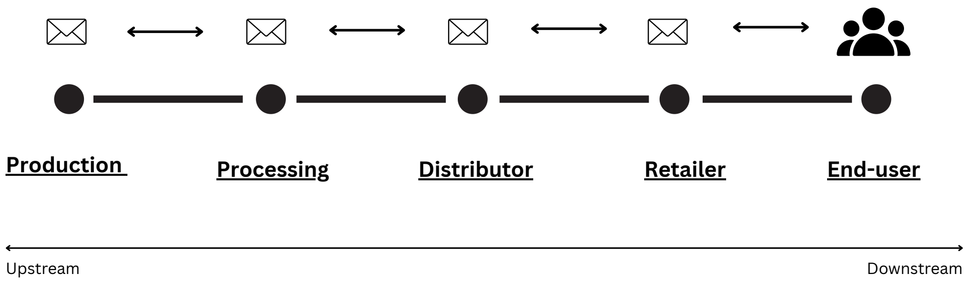

Figure 4 – “one step forward, one step backward”.

Source: Figure by the author based on Cammarano et al. (2023).

Despite legal enforcement, regulatory efforts remain insufficient (Tang et al., 2024). The complexity of global food networks and information asymmetry compromise real-time fraud detection and transparency, ultimately prolonging the time required to mitigate risks (Adamashvili et al., 2021;Mao et al., 2018;Treiblmaier & Garaus., 2022).

2.3. Blockchain Technology

Blockchain technology (BCT) is a decentralized and distributed ledger which records transactions in an immutable and transparent manner (Chandan et al., 2023; Guruswamy et al., 2022; Mercuri et al., 2021; Treiblmaier & Garaus, 2022). It accumulates sequentially linked data blocks secured by cryptographic hash functions, maintained by a network of nodes using a consensus mechanism (Mališić et al., 2023;Adamashvili et al., 2021). The consensus mechanism ensures agreement on transaction validity before data is recorded (Adamshvili et al., 2021; Katsikouli et al., 2021; Garaus & Treiblmaier, 2021). Once recorded, data cannot be altered without affecting previous blocks, guaranteeing security and trust (Panigrahi et al., 2024; Ellahi et al., 2024; Tang et al., 2024). Figure 5 demonstrates a typical flow of a blockchain transaction recorded into the BCT by Duan et al., 2024.

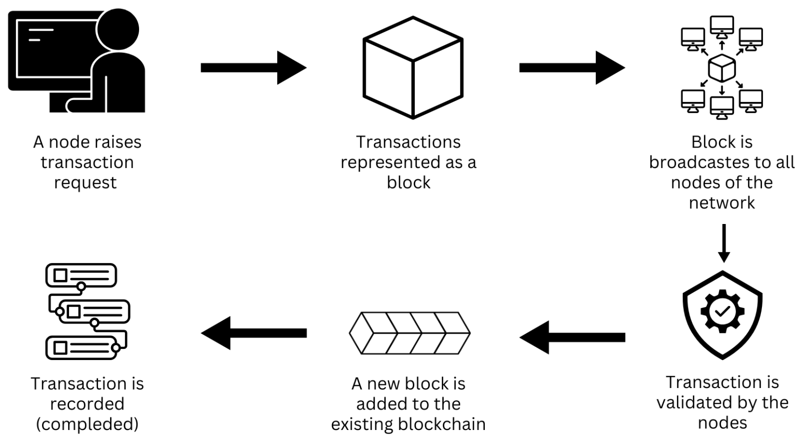

Figure 5 - The Process of Recording a Block into a Blockchain.

Source: Figure by the author based on Duan et al. (2024).

Historically, BCT originated in the 1990s with Haber and Stornetta's digital timestamping concept (Adamashvili et al., 2021), but Satoshi Nakamoto formally introduced it in 2008 as the backbone of Bitcoin (Nakamoto, 2008). Since then, its applications have expanded beyond cryptocurrency to other domains such as supply chain management, healthcare, and intellectual property protection (Bandinelli et al., 2023). Chandan et al. (2023) highlight blockchain's evolution in which the first generation enabled decentralized digital currencies, and the second includes smart contracts for automation, expanding the technology's capabilities beyond digital currencies. More recently, the third emphasizes scalability, interoperability, and governance improvements, which reflects its application in non-financial industries such as SC management, healthcare, and food safety. BC's evolution demonstrates its potential to unlock new opportunities for innovation and transform the global SC (Mao et al., 2018). Table III describes the distinction between traditional databases and blockchain by Hisham et al. (2022).

Table III - Traditional Database vs. Decentralized Database.

Characteristic	**Database**	**Blockchain**
Architecture	Centralize	Decentralized
Performance	Connects to a centralized server.	Traceable block transaction.

Downtime for system update	Add data to the database without tracing.	No system downtime. Other BC nodes can update at any time.
System backup	Admin has complete access to the database.	Through SM. Permission or access is protected and encrypted. No admin.
DDoS	The entire systems hang and shuts down.	One node down, other nodes are still running.
Application development and deployment	Require web server hosting services; no direct programming in the dataset; only SQL programming for data analysis.	All programming and data are in one place via SM programming; no hosting services; everything is executed by BC nodes.

Source: Table by Hisham et al. (2022).

As described in Table III, blockchain's decentralization distributes data across a peer-to-peer network, guaranteeing no single entity or authority controls the system (Tang et al., 2024; Goyal et al., 2023). Each node maintains a copy of the ledger, enhancing transparency and reducing risks associated with fraud (Garaus & Treiblmaier, 2021). Furthermore, this structure mitigates single points of failure and strengthens security by making unauthorized alterations or attempts to delete data nearly impossible (Bager et al., 2022). Figure 6 illustrates the contrast between centralized and decentralized networks.

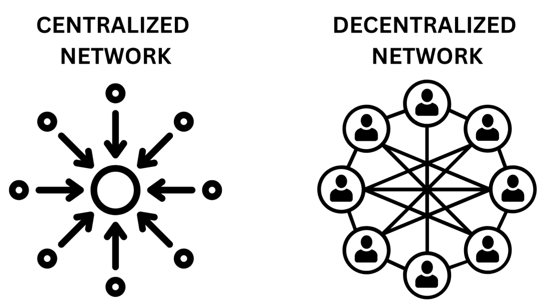

Figure 6 - Centralized network and decentralized network.

Source: Figure by the author.

In fact, blockchain mitigates security threats and unauthorized modifications by leveraging cryptographic algorithms and consensus mechanisms (Chandan et al., 2023). It fortifies traceability and goes beyond the traditional EU Reg. 178/2002 "one step forward, one step backward" traceability approach (Stranieri et al., 2020). Table IV describes the differences between the existence FSC and BC-based FSC by Sri Vigna Hema & Manickavasagan (2024).

Table IV - Comparison of existing FSC and BC-based FSC.

Features	Traditional FSC	BC-based FSC
Transparency	Limited	High
Traceability	Slow and error-prone	Real-time and accurate
Data security	Vulnerable to tampering	Immutable and secure
Efficiency	Manual processing and slower	Automated and faster
Cost	Higher due to intermediaries	Reduced by eliminating intermediaries
Trust	Depended on third parties	Decentralized verification
Response to issue	Delayed	Immediate
Quality assurance	Inconsistent and Manual check	Consistent quality check
Auditability	Complex and time-consuming	Simplified and instantaneous

Source: Table by Sri Vigna Hema & Manickavasagan (2024).

2.3.1. Different Types of Blockchain Technology

Blockchain technology can be categorized based on the degree of decentralization and access control required for participation. The three primary types are (i) public blockchains, (ii) consortium blockchains, and (iii) private blockchains. Each has distinct characteristics that determine its appropriateness for various applications, as shown in Figure 7.

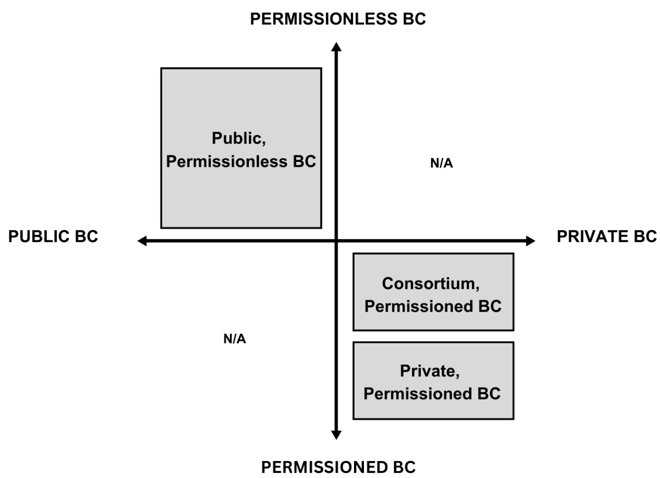

Figure 7 - Types of Blockchain Networks

Source: Figure by the author.

Public blockchains such as Bitcoin and Ethereum are fully decentralized networks in which anyone can participate in transaction validation and consensus (Goyal et al., 2023).

Consortium blockchains operate under a partially decentralized model, where pre-approved nodes validate transactions (Sidarto & Hamka, 2021). Private blockchains are fully permissioned and controlled by a single entity that governs access and transaction validation (Patro et al., 2022; Goyal et al., 2023). Nevertheless, public blockchains often use Proof of Work or Proof of Stake (Tang et al., 2024), while private and consortium blockchains rely on Byzantine Fault Tolerance or RAFT for efficient consensus (Goyal et al., 2023). Consortium blockchains are preferred in supply chain management due to their scalability and privacy (Chandan et al., 2023; Rogerson & Parry, 2020). Examples include Hyperledger Fabric, which ensures participant anonymity while maintaining accountability (Mao et al., 2018). As BCT evolves, Tang et al. (2024) note that developing hybrid models combining public and private blockchain features may offer optimized solutions.

3. METHODOLOGY

3.1. Research Design

This dissertation employs a systematic literature review (SLR) to synthesize research on blockchain technology in combating food fraud. SLRs provide a transparent, reproducible approach to evaluating scientific evidence, minimizing bias, and ensuring replicability (Lamé, 2019). Following Lamé (2019) 8-step SLR process, this dissertation formulates research questions, applies inclusion and exclusion criteria, selects and assesses studies, extracts and analyses data, and interprets results. To ensure rigor and avoid cherry-picking data, the review adheres to the PRISMA 2020 guidelines, which improve transparency and reporting standards for systematic reviews (Page et al., 2021).

3.2. Data Collection Process

The search used two academic databases, Web of Science and Scopus to achieve a comprehensive literature review. The keywords were developed based on the research questions. Boolean operators such as "AND" and "OR" were utilized to construct a search string that maximized the retrieval of relevant articles. Thus, the search string used with Boolean operators on both databases was: (Blockchain OR Distributed Ledger) AND (Food Fraud) AND (Food Supply Chain) AND (Transparency OR Traceability). Furthermore, the keywords were developed not to constrain but rather to broaden the search and gather a comprehensive set of relevant studies, including papers with slightly different scopes but related aspects that could still provide insightful data to answer the research questions.

3.3. Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were developed to ensure the articles' relevance and quality. The inclusion criteria included that the articles must be written in English, open access, focus on the application of BCT within the FSC or agriculture sector, explicitly address the issue of food fraud (RQ1), and discuss barriers or challenges associated with the adoption of BCT in the FSC (RQ2). Conversely, articles that only briefly mentioned BC and FSC without addressing food fraud and those that did not meet the minimum quality assessment criteria presented in Table V were excluded from the review.

Table V - Minimum Quality Assessment Criteria.

Criteria	**Description**
Relevance	The article must explicitly examine the application of BCT within the FSC or agricultural sector, ensuring its relevance to food traceability and transparency.
Clarity	The article must clearly define its research objective, including the problem it addresses and contribution to knowledge.
Addressing RQ1	For inclusion under RQ1, the article must examine food fraud within the FSC, particularly in relation to transparency and traceability using BCT.
Addressing RQ2	For inclusion under RQ2, the article must discuss the barriers and/or challenges associated with BC adoption in the FSC.

3.4. PRISMA

The database searches yielded 96 articles from WoS and Scopus. After removing 11 duplicate records, 85 articles were screened based on their titles and abstracts, excluding six articles out of scope. In the following full-text screening phase, 79 articles were sought for retrieval. 2 reports could not be retrieved, resulting in 77 articles assessed for eligibility. In this phase, 28 articles from WoS and 13 from Scopus were not open access, while two articles (one from each database) were not in English, resulting in their exclusion. Ultimately, 36 articles met the inclusion criteria and were included in the SLR. The article selection process is shown in Figure 8, a PRISMA flowchart showing the number of articles identified, duplications, screened, included and excluded, and the final sample included in the review.

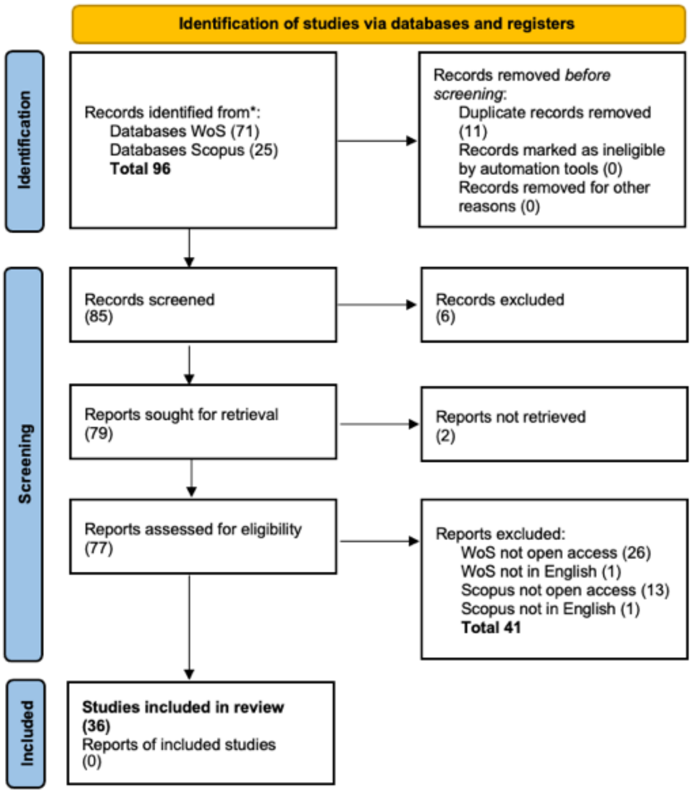

Figure 8 - Prisma Flowchart.

3.5. Material Collection

The temporal distribution of the selected studies from 2018 to 2024 is illustrated in Figure 9. Although BCT was initially introduced in 2009 as the backbone technology of Bitcoin, its application within the FSC has gained traction only in recent years. The findings indicate a rising research interest in this domain, with a notable increase in publications from 2020 onwards. The highest number of studies was published in 2024 (11 publications), followed by 2022 (10 publications) and 2023 (7 publications), reflecting an accumulation trend in scholarly engagement on this topic. Additionally, a geographical analysis of the included studies is shown in Figure 10. It highlights Italy as the leading country in BC research related to the FSC, with eight publications. India follows with four publications, the United Kingdom with three publications, and several other nations contributing to the growing body of literature. A more detailed breakdown of publications per country is provided in Appendix 1.

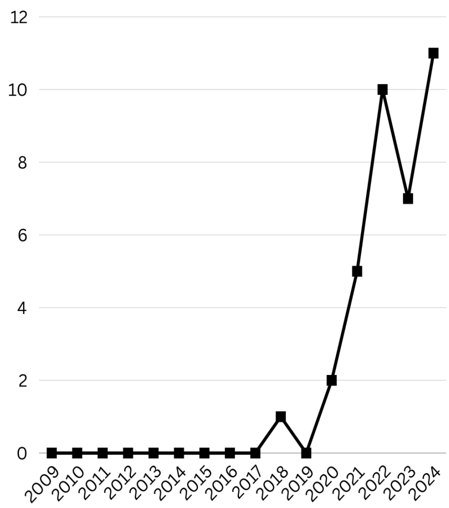

Figure 9 - Number of Yearly Publications.

Source: Figure by the author.

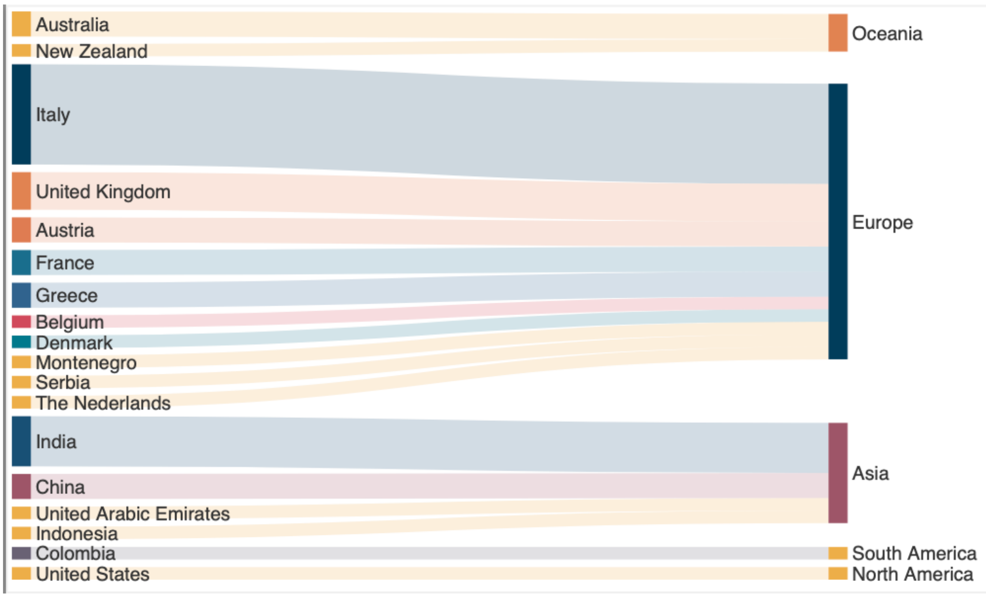

Figure 10 - Sankey Diagram of Publications by nations and continents.

Source: Figure by the author.

3.6. Data Analysis Method

This review employs thematic analysis (TA) to identify patterns across qualitative data. TA is a widely used method for organizing meaning within datasets, following Braun et al. (2019) six-phase approach: data familiarization, coding, theme development, theme review, definition, and reporting. This iterative process ensures that emerging themes align with research questions RQ1 and RQ2. To analyze barriers to blockchain adoption, the review applies the Technology, Organization, and Environmental (TOE) framework (Tornatzky et al., 1990). TOE examines how technological, organizational, and environmental dimensions influence innovation adoption. The technological context includes existing and emerging technologies, the organizational context considers firm structure and resources, and the environmental context factors in market competition and regulatory influences (Baker, 2011; Oliveira & Martins, 2011). Data was managed using Mendeley and Microsoft Excel, with duplicates removed and themes systematically categorized through color coding. A comprehensive list of the 36 studies included in this review is presented in Appendix 2, along with the studies that address RQ 1, RQ 2, or both.

4. Results and Discussion

In this chapter, the results and discussion are provided and further concluded in Chapter 5. Through thematic analysis, RQ 1 addresses how blockchain can enhance traceability and transparency in the food supply chain to combat food fraud. Traceability is first discussed, followed by transparency to answer the research question more systematically. Additionally, the review identifies complementary technologies from the literature that significantly elevate the efficiency of traceability and transparency when integrated with BCT. To answer RQ 2 about the key barriers to blockchain adoption in the FSC, both thematic analysis and the TOE framework were utilized to provide a comprehensive analysis, in which 14 barriers were identified.

4.1. Research Question 1

The modern food supply chain is complex, globally interconnected, and involves numerous stakeholders, making transparency and traceability in the FSC a global issue (Ellahi et al., 2024). By the same token, consumers increasingly demand reliable information regarding food products' origin, quality, and handling. However, traditional FSCs suffer from fragmented, siloed, and often unreliable data systems, creating opportunities for food fraud. The absence of transparency cultivates information asymmetry, in which specific actors possess more information than others, giving them an upper hand. This compromises trust among stakeholders and makes the supply chain vulnerable to fraudulent practices, which not only affect consumer confidence and trust but also jeopardize public health (Chiaraluce et al., 2024). To address these challenges, BCT has emerged as a promising tool for enhancing traceability and transparency in the FSC. Initially conceptualized by Nakamoto in 2008, BC is a public immutable ledger that records transactions in cryptographically linked blocks through decentralized consensus mechanisms. This decentralized nature of BC means that no single entity controls the data, which reduces the risk of data breaches or tampering (Duan et al., 2024). The structure of BC ensures that data cannot be altered without the consensus of the nodes, thus enhancing data integrity and mitigating practices associated with fraud (Garaus & Treiblmaier, 2021; Mercuri et al., 2021).

As a decentralized and distributed ledger, BC provides an immutable and end-to-end traceability tool, enabling data of the food products to be trace and tracked across their entire journey from farm to table (Goyal et al., 2023; Treiblmaier & Garaus, 2022; Zheng et al., 2023). Each transaction is securely stored on an immutable ledger, which prevents manipulation after data entry (Adamshvili et al., 2021). With shared access to transaction records, SC actors can verify the history and authenticity of food products, thus reducing opportunities for fraud (Treiblmaier & Garaus, 2022). Decentralized verification ensures that all participants share access to the same verifiable records, hence reducing the need for intermediaries and vulnerabilities associated with fraud (Zarba et al., 2024). The system creates a single point of truth accessible to all actors in the network, ergo cultivating information symmetry and mitigating opportunistic behaviour (Bager et al., 2022; Katsikouli et al., 2021;Patro et al., 2022;Rogerson & Parry, 2020).

BC guarantees accurate product tracking and verification of authenticity and quality (Guruswamy et al., 2022; Panigrahi et al., 2024), thus pinpointing fraudulent practices and improving fraud prevention strategies (Garzón et al., 2024). It ensures alignment between actual product characteristics and label information, which is namely valuable for high-value or geographically verified products, such as Protected Designation of Origin (PDO), Protected Geographical Indication (PGI), and Traditional Specialty Guaranteed (TSG) (Adamashvili et al., 2021; Maritano et al., 2024). BC has already been successfully used to authenticate products such as extra virgin olive oil (Singh & Sharma, 2022; Vitaskos et al., 2024), dairy products (Melissari et al., 2024), and wine (Rogerson & Parry, 2020), but it also supports ethical sourcing claims (Jellason et al., 2024) and organic certification verification. For instance, in the wine industry, Adamshvili et al. (2021) note that BC ensures secure storage of records related to grape origin, production processes, and transaction history, which is critical given the EU's regulation regarding wines with and without designation of origin. Thus, it helps verify compliance with regulatory standards (Adamshvili et al., 2021). Additionally, BS supports both forward (downstream) and backward (upstream), allowing for the rapid identification and isolation of contaminated or fraudulent products at any point in the SC (Duan et al., 2024).

Transparency is an essential attribute of effective traceability, as transparency ensures that traceability data is reliable and credible (Zarbà et al., 2024; Panigrahi et al., 2024). BC enhances transparency by recording all transactions in an immutable distributed ledger, thus mitigating fraud and increasing SC accountability (Bandinelli et al., 2023; Mohammed et al., 2023). Each transaction is verified by all the nodes in the network before it is recorded, which adds additional layer of security, and prevents fraudulent products from entering legitimate supply chains (Khanna et al., 2022). Patro et al. (2022) note that when actors know that their actions are traceable and verifiable, there is a higher chance that they will adhere to best practices in food safety and ethics. Similarly, Stranieri et al. (2020) highlight that increased accountability discourages opportunistic and unethical behaviour. Furthermore, verifiable transparency significantly influenced consumer trust and the perceived credibility of food labels (Bandinelli et al., 2023; Mohammed et al., 2023).

Due to traditional traceability systems' reliance on manual data entry, they are often vulnerable to errors, manipulation, and inefficiencies (Sidarto & Hamka, 2021). BC, on the other hand, offers an immutable record-keeping system, which is notably valuable in complex global supply chains involving numerous actors (Goyal et al., 2023). Nevertheless, BC supports compliance with food safety standards, such as EU Reg. 178/2022, ISO 22000, Hazard Analysis and Critical Control Points (HACCP), and U.S. FDA Food Safety Modernization Act (Guruswamy et al., 2022; Tang et al., 2024). Beyond traditional food safety applications, blockchain holds a significant role in religious dietary compliance. Sidarto and Hamka (2021) highlight its effectiveness in guaranteeing Halal food traceability, providing credibility to businesses that must adhere to religious food standards, thus helping consumers verify whether food products meet specific religious and ethical standards before purchase.

Noteworthy, several real-world case studies demonstrate BC's effectiveness in improving traceability and mitigating food fraud. For instance, IBM's collaboration with Walmart mitigated mango and pork SC tracking time from several days to just 2.2 seconds (Mohammed et al., 2023; Singh & Sharma, 2022). Similarly, BC integration in the Italian wine industry enables wineries to verify vintages, production methods, and geographical origins (Malisic et al., 2023). BC has successfully tracked coffee bags from Colombian producers to Swedish importers in the coffee SC, ensuring transparency and sustainability compliance (Bager et al., 2022). In the seafood industry, similar systems using BCT have been adopted, in which the technology is used to verify the sustainability and legality of fishing practices (Patro et al., 2022). Furthermore, Melissari et al. (2024) highlight the dairy industry in which BC secures feta cheese production by encoding production standards into smart contracts. Additionally, major retailers such as Carrefour and Walmart have implemented BC-based traceability labels on poultry, eggs, and fresh products, preventing fraud and foodborne illnesses while improving consumer confidence (Treiblmaier & Garaus, 2022). Notably, several studies demonstrate that increased transparency positively influences consumer perception of food quality and willingness to pay, particularly for products from lesser-known brands (Garaus & Treiblmaier, 2021; Bandinelli et al., 2023).

4.1.1. Complementary Technologies with Blockchain Technology

Bager et al. (2022) emphasize that BCT is not a silver bullet as it relies on additional technologies to provide efficient traceability and transparent systems to address complex challenges such as food fraud in the FSC. The effectiveness of BCT in the FSC is magnified when integrated with complementary technologies such as the IoT, smart contracts, AI, ML, and cloud computing, as illustrated in Figure 11 with the respective authors. Although BC provides a secure and immutable ledger, scholars note that it is insufficient for ensuring comprehensive food traceability on its own. Thus, integrating BCT with real-time data collection and automation tools accelerates its ability to provide effective traceability systems and transparency (Goyal et al., 2023;Maritano et al., 2024;Vitaskos et al., 2024;Zheng et al., 2023).

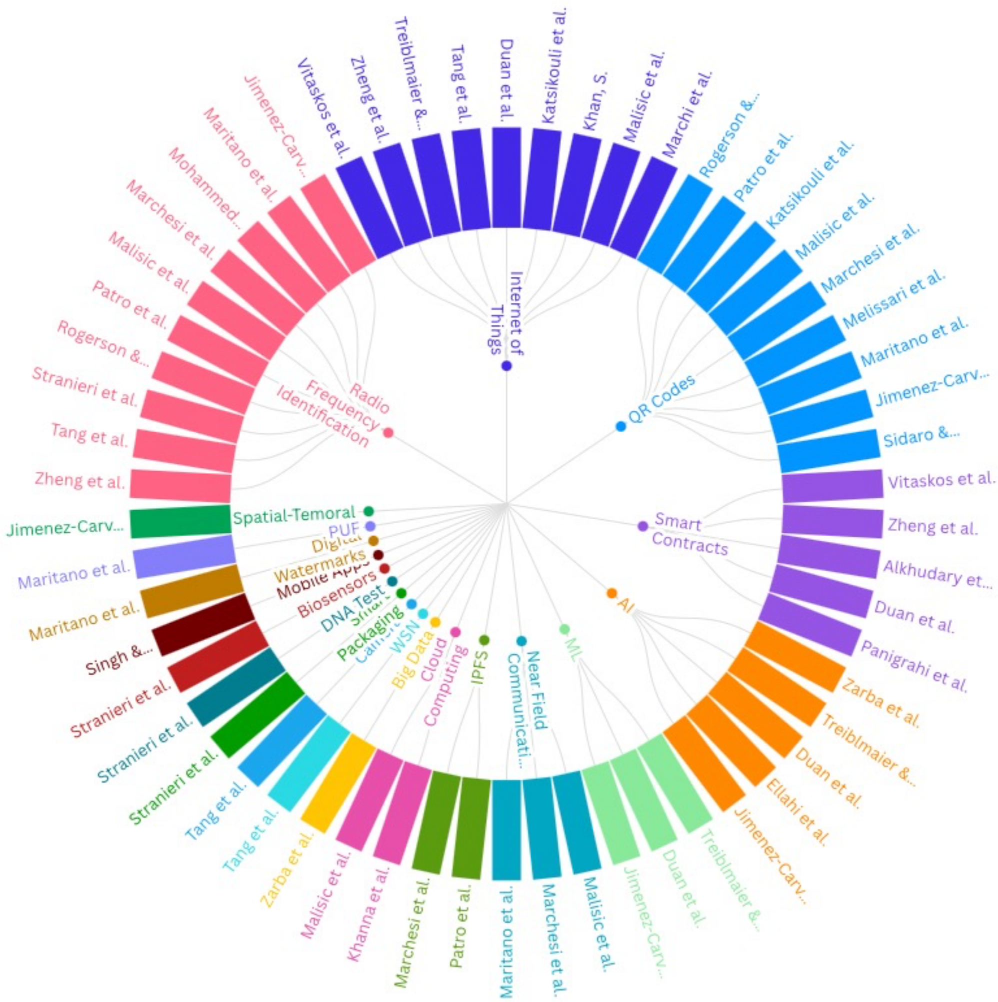

Figure 11 Radial Diagram of Complementary Technologies with BCT.

Source: Figure by the author.

IoT devices are essential in real-time monitoring of FSC conditions. Duan et al. (2024) highlight how IoT devices securely record real-time data onto BC networks through smart contracts (SM). These contracts automate compliance enforcement, reducing reliance on intermediaries, reducing costs, and improving efficiency. For instance, IoT sensors continuously track temperature during processing in the olive oil industry. If the temperature exceeds a predefined threshold, BC-based SM can automatically trigger alerts and make the information accessible to all stakeholders (Tang et al., 2024). Similarly, RFID sensors and wireless networks can monitor crucial parameters such as temperature, humidity, and location during transportation, guaranteeing that food products remain in their optimal conditions (Malisic et al., 2023).

Beyond real-time monitoring, SM are instrumental in automating transactions and enforcing regulatory compliance (Alkhudary et al., 2022; Panigrahi et al., 2024). In SC management, these contracts can be programmed to release payments when only quality standards are met, hence reducing fraud risks and eliminating manual verification processes. AI and ML further fortify blockchain-enabled FSC management by providing predictive analytics, anomaly detection, and automated decision-making (Treiblmaier & Garaus, 2022). AI-driven algorithms analyse recorded data on the BC to identify patterns, predict disruptions, and improve logistics (Zarbà et al., 2024). These technologies are particularly notable in processing the influx of IoT-generated data recorded on BC system. By identifying inefficiencies, detecting potential fraud, and optimizing supply chain processes, AI and ML not only improve transparency but also contribute to overall food security (Ellahi et al., 2024). This capability is namely beneficial for fraud detection, as AI can recognize opportunistic patterns that might otherwise go unnoticed in traditional systems. Additionally, ML elevates BC data analysis through continuous learning, increasing accuracy as more data is recorded and processed (Duan et al., 2024).

Nonetheless, RFID tags and QR codes serve as a bridge for linking physical products to their digital records on BC networks. Several scholars reinforce the role of RFID technology in tracking product movements throughout the FSC, as it enables real-time data capture and verification, reducing fraud risks and enhancing food authenticity (Maritano et al., 2024; Stranieri et al., 2020). For instance, in the seafood SC, RFID tags can store crucial data such as species, origin, and batch details, which are then securely recorded on the BC (Patro et al., 2022). Similarly, QR codes provide a low-cost solution for consumers to access BC-verified product histories through smartphone applications (Melissari et al., 2024; Singh & Sharma, 2022). Businesses such as Techrock and Demeter have embedded RFID tags, which the former offers assurance to parents regarding the provenance of infant formula. Their products are protected by smart packaging, including a small wire embedded in the product label, which acts as an antenna for an RFID tag. Consumers have access to their data through a smartphone app, which authenticates the product within a few seconds of being scanned. Every scan further creates a new authentication key, which is stored on a public Hyperledger-based BC. By storing authentication keys on its BC and allowing consumers to scan a QR code, Techrock not only addresses counterfeiting but also empowers consumers by ensuring that the product they are purchasing is authentic. Additionally, TraSeable with World Wildlife Fund (WWF) uses QR codes on product labels to promote transparent fishing practices, as well as allowing consumers to scan and verify authenticity (Rogerson & Parry, 2020). Nevertheless, Maritano et al. (2024), Malisic et al. (2023), and Mohammed et al. (2023) demonstrate that RFID and NFC tags have been successfully integrated into BC systems across various industries, including dairy, meat, seafood, wine, and olive oil.

Moreover, as IoT devices integrated with BC generate an influx of information, Garzon et al. (2024) note that cloud computing can significantly contribute to managing and processing data. Cloud-based virtual storage systems enable scalable and accessible data management, supporting the computational needs of BC-integrated SC (Khanna et al., 2022). Storing large files directly on the BC is costly and inefficient, making decentralized storage solutions such as the InterPlanetary File System (IPFS) a viable alternative. IPFS enables peer-to-peer storage, where only the hash values of large files, such as product images or videos, are stored on the BC, ensuring data integrity along with mitigating on-chain storage costs (Marchesi et al., 2022; Patro et al., 2022).

4.2. Research Question 2

This chapter aims to answer the second research question utilizing the TOE framework, as illustrated in Figure 12.

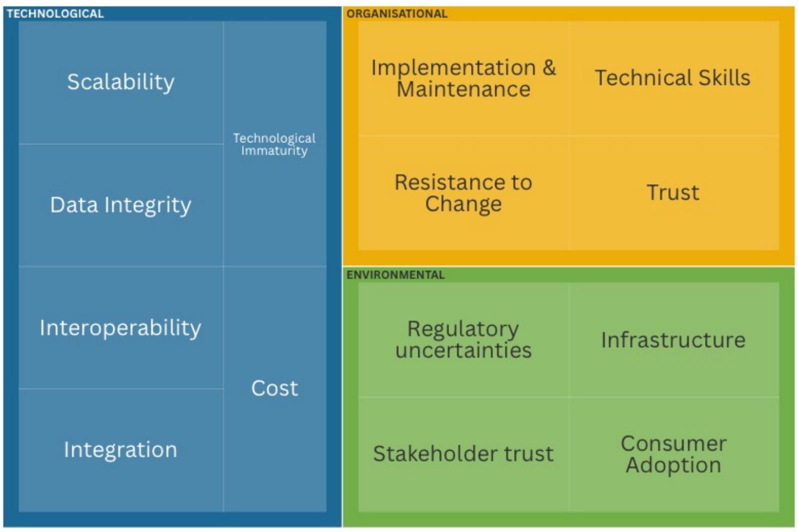

Figure 12 - TOE Framework with The Identified Barriers.

Source: Figure by the author.

4.2.1. Technological Barriers

Scalability

Scalability is one of the primary barriers to BC adoption in the FSC due to increasing transaction volumes and storage demands. Public BC platforms like Ethereum struggle with block size and transaction throughput limitations (Tang et al., 2024). Similarly, Mohammed et al. (2023) note that as the number of users and transactions grows, the system requires all nodes for validation, which affects scalability and increases operational costs. The generation of a vast amount of data with IoT integration adds an additional layer of strain on the scalability issue (Singh & Sharma, 2022; Mao et al., 2018).

Interoperability

The absence of universal blockchain standards deters seamless integration with existing SC management systems (Katsikouli et al., 2021), which is further elaborated in the section on environmental barriers. Differences in programming languages and network protocols create data silos and compatibility challenges (Mohammed et al., 2023). Proposed solutions, such as interconnected SM aim to improve cross-platform communication. However, the infrastructure remains inadequate to support large-scale data exchange between BC networks and other digital platforms (Vitaskos et al., 2024; Garzón et al., 2024).

Data Integrity and Security

Although blockchain ensures immutability, it does not guarantee data accuracy. False or manipulated inputs can still be recorded without authentication (Alkhudary et al., 2022). IoT integration introduces additional security risks, including weak authentication protocols and insecure data transmission (Vitaskos et al., 2024). Additionally, SM can contain bugs and vulnerabilities, necessitating rigorous testing with tools such as SmartCheck and Oyente (Patro et al., 2022).

Integration with Existing Systems

Many FSC actors still use traditional practices such as paper-based records or closed digital systems (Vitaskos et al., 2024). Not to mention, transitioning to BCT requires infrastructure investment and workforce training (Zheng et al., 2023), which is further highlighted in the subsequent section on organizational barriers. Nevertheless, the complexity of incorporating BC into existing operations creates technical barriers, as it requires modifications to their software architecture. Patro et al. (2022) note that sectors such as fisheries, which often use centralized data management, must overhaul existing frameworks, leading to high costs and implementation challenges.

Technological Maturity

Many BC applications remain in pilot phases rather than being fully integrated into supply chains (Stranieri et al., 2020). Similarly, implementing IoT-based BC solutions is still in early development, compromising their widespread adoption (Hassoun et al., 2023). Thus, Bandinelli et al. (2023) emphasize the need for continued academic research to enhance usability and efficiency.

Cost and Computational Constraints

BC requires high processing power and energy consumption, constraining its feasibility for large-scale adoption (Chiaraluce et al., 2024). Noteworthy, public BCs involve high storage costs, making them impractical for managing large datasets (Marchesi et al., 2022). Integrating IoT and AI adds complexity, requiring advanced infrastructure that may not be available across all supply chains (Ellahi et al., 2024). Poor connectivity further deters reliable data transmission in remote areas, such as underground wine cellars and certain developing economies (Tang et al., 2024; Malisic et al., 2023). This challenge will be further elaborated in the section on environmental barriers.

4.2.2. Organizational Barriers

Implementation and Maintenance Costs

Blockchain adoption requires major financial investment in hardware, software, infrastructure, and training, making it particularly challenging for SMEs (Bandinelli et al., 2023; Ellahi et al., 2024; Adamashvili et al., 2021). Costs include transaction fees, data storage, and IT infrastructure, with uncertain short-term returns on investment (Garzón et al., 2024; Tang et al., 2024). Thus, integrating BC with existing systems requires costly software development and data migration (Zheng et al., 2023).

Technical Expertise and Digital Literacy

The scarcity of skilled professionals with expertise in cryptographic protocols, consensus mechanisms, and smart contracts compromises its adoption (Guruswamy et al., 2022;

Khanna et al., 2022). Many farmers and SMEs have limited digital literacy, making blockchain adoption challenging (Chandan et al., 2023; Tang et al., 2024). Manual data input errors also threaten the reliability of BC records (Jellason et al., 2024; Melissari et al., 2024).

Resistance to Change and Organizational Inertia

Many businesses hesitate to transition from traditional record-keeping due to fears of operational disruptions (Ellahi et al., 2024; Garzón et al., 2024). Industries such as wineries and small agricultural cooperatives show low adoption rates due to entrenched practices (Chiaraluce et al., 2024). BC requires process standardization and governance structures, which increase costs and complexity (Katsikouli et al., 2021). Concerns over job displacement and automation further fuel resistance (Garzón et al., 2024).

Trust and Data Confidentiality Concerns

Data confidentiality in decentralized networks and fear of exposure to competitors influence the adoption rate (Jellason et al., 2024; Singh & Sharma, 2022; Mališić et al., 2023). Additionally, stakeholders may lack trust in the reliability of blockchain-recorded data, namely since BC immutability makes it difficult to correct errors or manipulated data, posing uncertainty to traceability and food safety (Alkhudary et al., 2022; Melissari et al., 2024). BC's association with cryptocurrencies and media criticism has contributed to setbacks among the stakeholders (Rogerson & Parry, 2020; Zarbà et al., 2024).

4.2.3. Environmental Barriers

Regulatory Uncertainty and Legal Challenges

The absence of clear regulations on data protection, intellectual property, and trade laws creates uncertainty for businesses (Mohammed et al., 2023; Vitaskos et al., 2024). The regulatory landscape varies across jurisdictions, complicating standardization and global adoption (Chiaraluce et al., 2024; Tang et al., 2024). Data ownership and confidentiality concerns further discourage stakeholders from sharing information (Adamashvili et al., 2021; Garzón et al., 2024). The absence of universal blockchain standards adds another layer of complexity, limiting interoperability across SCs (Katsikouli et al., 2021; Khanna et al., 2022). Bandinelli et al. (2023) note that until legal and regulatory clarity is achieved, stakeholders in the FSC may hesitate to invest in blockchain-based traceability systems.

Infrastructure Limitations

Reliable internet, electricity, and computing power are essential for BC operations but remain inconsistent in remote and developing economies (Garzón et al., 2024; Tang et al., 2024). High computational demands increase costs in areas with limited information and communication technology infrastructure (Guruswamy et al., 2022). Energy-intensive consensus mechanisms such as Proof of Work also raise sustainability concerns, necessitating more energy-efficient BC solutions (Tang et al., 2024).

Stakeholder Collaboration Challenges

Various SC stakeholders vary in digital literacy and technological capabilities, making collaboration challenging (Zarbà et al., 2024). Free-rider behaviour is another concern, in which some actors benefit from BC mechanisms without contributing themselves, thus compromising the overall system (Zheng et al., 2023). Additionally, traditional businesses may resist BC adoption due to fears of disrupting existing models (Garzón et al., 2024; Tang et al., 2024). Nevertheless, Khan (2022) notes that large corporations could monopolize BC networks, further limiting accessibility for SMEs.

Consumer Awareness and Adoption

As the backbone technology for traceability and transparency systems, BCT benefits become less explicit to consumers (Treiblmaier & Garaus, 2022). Limited consumer awareness about its role in food safety and transparency contributes to skepticism (Bandinelli et al., 2023). For instance, a case study conducted by Bandinelli et al. (2023) revealed that a large portion of the consumers in Italy do not understand how blockchain can elevate food safety and transparency, thus leading to skepticism about its added value. Additionally, higher costs of BC-enabled products may affect consumer willingness to pay (Chiaraluce et al., 2024; Rogerson & Parry, 2020). Notably, overloading consumers with excessive product information may diminish the effectiveness of BC-based labelling systems (Stranieri et al., 2020). Table VI in the following section summarizes the results from RQ1 and RQ2.

Table VI – Summary of the Results

Research Question	Summary of result	Description
RQ1: *How can Blockchain enhance traceability and transparency in the food supply chain to combat food fraud?*	Provides end-to-end traceability and a decentralized system.	Movement of food product can be tracked and traced from farm to table, both downstream and upstream. With decentralization, no single entity controls the data, ergo all actors in the network share access to the same verifiable data.
	Ensures data immutability and stimulates information symmetry.	Once data gets recorded in the system, it becomes immutable and contributes to a single source of truth; it cannot be altered or deleted without consensus from the nodes in the network.
	Enables verification of food origin, quality, and handling.	With shared access to transactions records, actors in the network can verify the history and authenticity of food products; increase accountability.
	Through transparent labelling methods such as QR codes, consumer gets empowered.	Consumers get access to BC-verified product histories through smartphone applications like scanning a QR code on a food product.
	Integration with complementary technologies such as IoT, smart contracts, AI, ML, and cloud computing increase's efficiency, reliability and automation.	BCT is not a silver bullet as it relies on additional technologies to provide efficient traceability and transparent system. The effectiveness of BCT in FSC is magnified when integrated with these complementary technologies.
RQ2: *What are the key barriers to blockchain adoption in the food supply chain?*	Technological Barriers	Scalability.
		Interoperability.
		Data integrity and security.
		Integration with existing systems.
		Technological maturity.
		Cost and computational constrains.
	Organizational Barriers	Implementation and maintenance costs.
		Technical expertise and digital literacy.
		Resistance to change.
		Trust and data confidentiality concerns.
	Environmental Barriers	Regulatory uncertainty and legal challenges.
		Infrastructure limitations.
		Stakeholder collaboration.
		Consumer awareness and adoption.

4.3. Discussion

To tie back to where we initially began, in the words of Tornatzky et al. (1990): *"neither life nor innovation is at all simple nor linear."* Technological innovation is neither a single event nor even a small number of discrete events but involves a rich embroidery of events:

> From initial idea generation, which may or may not derive directly from scientific research to widespread use of technological innovations by an appropriate population of users, the time can range from months to decades

In: Tornatzky et al (1999), p. 27.

This undoubtedly echoes BCT as a cutting-edge technology in the FSC. Once data is recorded on the BC with the approval of all nodes in the network, it becomes immutable and decentralized, enhancing traceability and accountability among SC actors. Its distributed ledger system ensures that all participants in the network have access to the same verified data, ergo increasing transparency. In fact, BCT presents an interesting paradox when compared to traditional systems. In a BC network, the reliability and security of the system increase as more actors join, strengthening data integrity and making it more resilient through decentralized consensus. Controversy, traditional supply chain systems become more vulnerable to fraud as the number of actors increases due to fragmented data management, information asymmetry, and reliance on centralized control. The more food products change hands, the more vulnerable the FSC becomes, which creates opportunities for bad actors to exploit gaps in the system and introduce fraudulent products into a legitimate supply chain. This practice is namely lucrative in high-value supply chains.

However, as identified in the literature, BCT is not a silver bullet. Additional technologies such as QR codes, can be integrated with BC to enhance transparency and empower consumers. By allowing consumers to scan a QR code, they can trace a product's journey and cultivate trust in the FSC, favoring consumers and regulatory authorities. Furthermore, smart contracts can automate agreements, trigger alerts, and notify stakeholders. At the same time, real-time data collection through IoT, cloud computing, and RFID sensors allows for recording crucial information, which can be stored on the BC and analyzed using AI and ML for deeper insights. Off-chain solutions and other complementary systems have been proposed to address storage challenges.

Furthermore, 14 barriers to blockchain's adoption have been identified and introduced using the TOE framework, spanning technological, organizational, and environmental dimensions, which often influence one another. The technological barriers include scalability, as BC networks process an accumulated volume of transactions and store vast amounts of data. This creates computational constraints that impact efficiency and lead to higher operational costs. BCT requires substantial processing power and energy consumption, making its implementation resource intensive. Additionally, the absence of universal BC standards presents a major barrier. Differences in programming languages, consensus mechanisms, and network protocols create data silos and interoperability issues, hampering seamless integration into existing operations. The absence of standardization also complicates collaboration between stakeholders using different BC platforms. Moreover, BC and IoT-based solutions remain in their early stages, raising concerns about data integrity and security. The reliability of IoT sensors and the potential for data manipulation pose vulnerabilities to BC traceability systems, compromising trust in the technology's effectiveness.

The Organizational Barriers include high implementation costs, which create significant barriers, particularly for SMEs, which may struggle with the financial burden of data migration, software development, and infrastructure upgrades. Many businesses also have concerns about operational disruptions during the transition from traditional systems. Noteworthy, there is a scarcity of skilled professionals with expertise in BCT, which complicates the adoption process and increases reliance on external consultants. Data confidentiality concerns contribute to resistance, as businesses worry about exposing critical information to competitors.

Lastly, environmental barriers such as regulatory uncertainty remain a major barrier in the BC landscape. The absence of clear legal frameworks governing BC-based food traceability systems creates setbacks among stakeholders, as they face potential compliance risks without standardized guidelines. Additionally, BC relies on robust infrastructure, including stable internet connectivity, reliable electricity, and sufficient computing power. These resources may be scarce in remote and developing economies, making BC adoption impractical or financially unfeasible. BC's effectiveness in ensuring traceability and transparency further depends on active data sharing among all actors in the FSC. The free-rider problem arises when certain stakeholders benefit from BC without contributing data or resources, affecting the integrity of the system. Furthermore, since BC is the backbone technology of transparent and traceability systems, its tangible benefits are difficult to communicate effectively to stakeholders. Not to mention at the consumer level, limited awareness and understanding of BC's potential and added value within the FSC, as well as information overload further hinder its widespread adoption. Nevertheless, major corporations such as Walmart and Carrefour have been widely regarded in the literature as being at the forefront of BCT in the FSC. However, as Khan (2022) highlights, the power dynamic may affect SMEs by compromising their access to these systems, therefore risking the monopolization of BC networks by dominant actors.

The literature's findings solidify that BCT in the FSC is still in its early stages, and many businesses have consequently adopted a wait-and-see approach to the technology. Despite the low-hanging fruit approach and BC's early presence in the FSC, a cumulative body of literature proposes BC as a fruitful technology. More theoretical and empirical research is needed, resulting in a relatively untapped academic field. This is further discussed in chapter 5.3 on future research.

5. Conclusion and Future Research

5.1. Conclusion

This SLR employed a qualitative approach, utilizing academic databases such as WoS and Scopus, and followed the PRISMA 2020 guidelines, inclusion and excluding criteria, along with minimum assessment criteria. The analysis of the final sample of 36 studies, using thematic analysis and the TOE framework, revealed that blockchain technology presents a promising tool for enhancing end-to-end traceability in the food supply chain with its decentralized, immutable, and distributed ledger system. Conversely, traditional systems often rely on manual, paper-based data recording, making them centralized and error-prone. Not to mention, it becomes more challenging to pinpoint where incidents occurred, as well as vulnerable to exploitation by bad actors. On the other hand, BC enables the rapid tracing and tracking of products from farm to table, allowing stakeholders to verify data integrity. This increased transparency fortifies consumer trust and collaboration among supply chain actors. The findings from the literature also reinforced the benefits of integrating BC with complementary technologies, such as smart contracts, IoT, AI, ML, cloud computing, and sensors, to improve real-time data management and address the influx of data on the blockchain, along with its efficiency and storage capacity concerns. Integrating these technologies with BC can mitigate human error, fraudulent practices, and operational costs by minimizing reliance on intermediaries. However, the review identified 14 barriers to BC adoption, including technological (scalability, interoperability, data integrity, integration, technological immutability, and costs), organizational (implementation and maintenance costs, technical skills, resistance to change, and trust issues), and environmental (regulatory uncertainties, infrastructure, stakeholder trust, and consumer adoption) barriers. Although BCT is still in its early stages, its trajectory shows great promise. Beyond the FSC, it has the potential to be leveraged in various industries, making it a powerful tool to address not only challenges but also wicked problems related to sustainability and climate change.

5.2. Research limitations

This SLR acknowledges that no research is without limitations. The data harvest of this dissertation relied on previous literature published between 2018 and 2024, and the selection of keywords influenced which publications were extracted from the databases. Additionally, the inclusion and exclusion criteria and the minimum assessment criteria were based on the author's subjective decisions, which may introduce some bias. As the review utilized secondary data, future research would benefit from more empirical investigations to capture the rapid evolution of blockchain technology in the FSC. The author notes that a significant limitation is the exclusion of a great number of non-open access publications, which may have contained relevant information about the research questions that were thus overlooked.

5.3. Future research

Chapter 3.5 in this dissertation highlighted a growing academic interest in applying BCT within the FSC. However, several gaps in the existing literature have been uncovered, as illustrated in Table VII.

#	Research Gaps	Description
1.	Empirical studies.	Majority of the studies focus on theoretical aspects, thus there is a limited number of real-world case studies.
2.	BC adopting in difference food categories.	As the food sectors is highly diverse, BC adoption vary significantly between different food categories, as each face their distinct characteristics in term of fraud vulnerability, SC complexity and regulatory requirements.
3.	Non-technical factors.	Factors beyond technical factors which also influence adoption such as costs, market dynamics, infrastructure, trust, resistance to change, and digital literacy among stakeholders, along with legal and regulatory constraints should be further studied.
4.	BCs direct impact on various food fraud practices.	Transparency and traceability are commonly mentioned as key benefits, but their direct role in reducing different food fraud types is limited to a few studies.

Table VII - Summary of Research Gaps.

Notably, while there is a growing volume of research on the application of blockchain, namely in high-value supply chains, such as seafood, extra virgin olive oil, wine, dairy, and products with protected designations of origin (PDO) and protected geographical indications (PGI) claims, most studies mainly focus on blockchain's theoretical potential, with limited empirical validation. Consequently, future research should prioritize the absence of empirical studies demonstrating BC's effectiveness across specific food categories. Furthermore, the majority of existing research focuses on the technical aspects of blockchain, such as its architecture, data immutability, and transaction mechanisms, while giving limited attention to non-technical factors that influence adoption. As highlighted in Chapter 4.2 using the Technology-Organization-Environment (TOE) framework, these factors include organizational and environmental dimensions, such as implementation costs, market dynamics, infrastructure availability, trust, resistance to change, and digital literacy among stakeholders, along with legal and regulatory constraints. Nevertheless, although transparency and traceability are commonly highlighted as key benefits of blockchain in the FSC, a limited number of studies look further into its direct impact on addressing specific types of food fraud as highlighted in Chapter 2.1.

These gaps in the existing literature underline the need for more research on blockchain adoption in different food categories in the FSC, as well as how BC mitigates specific food fraud practices. Thus, future research would benefit from conducting more context-specific empirical studies. Such insight would be valuable for developing more tailored BC solutions aligned with the distinct challenges and opportunities of the global food system.

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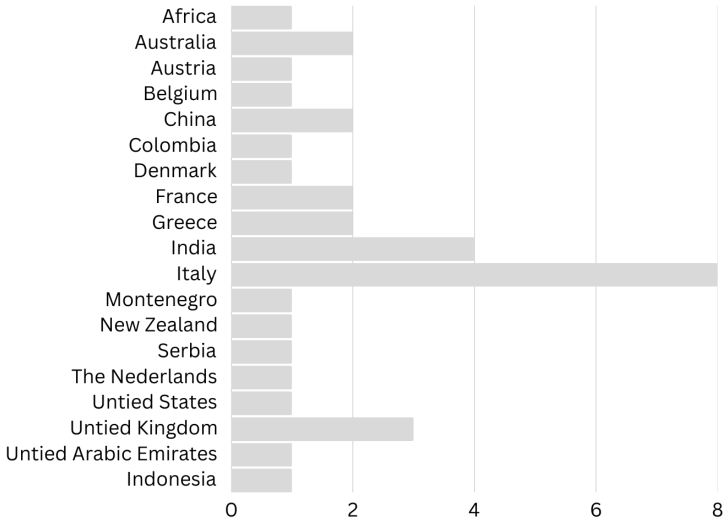
Appendices

Appendix 1 - Number of publications per country.



Appendix 2 - A comprehensive overview of studies included in the SLR.

#	Country	Year	Author(s)	FCS type(s)	Methodology	Objective	Findings	RQ Addressed
1	Italy	2024	Chiaraluce, G., Bentivoglio, D., Finco, A., Fiore, M., Contò, F., & Galati, A.	Wine and olive oil	Quantitative	A bibliometric review of research on BCT adoption, particularly in high-value supply chains prone to fraud. It examines studied aspects of BCT adoption, with a focus on economic implications and its operational impact on these supply chains.	Research on BCT in the FSC is growing, focusing on food safety and fraud. While wine is gaining interest, olive oil remains underexplored. BCT can enhance profitability and sustainability in agri-food, but further study is needed on its environmental and social impact, implementation costs, and consumer acceptance.	RQ1 and RQ 2
2	United Kingdom	2024	Duan, K., Onyeaka, H., & Pang, G.	Meat, seafood, eggs, dairy, leafy greens and chicken	Conceptual	Offers a comprehensive review of BCT's role in combating food fraud and enhancing food safety through literature analysis and case studies.	BCT can enhance food safety and quality through improved traceability and accountability. However, challenges like scalability, collaboration, and innovation must be addressed, along with advancing BC protocols and integrating IoT and AI to maximize its potential in the FSC.	RQ 1
3	New Zealand	2024	Ellahi, R. M., Wood, L. C., & Bekhit, A. E.-D. A.	Not specified	Qualitative	A systematic review of BCT applications in FSC, highlighting underutilized potential.	BCT enhances transparency, traceability, and security in FSC, yet key areas remain underexplored, such as food donation, SC financing, animal welfare, waste management, and data analysis. A proposed framework guides future research, emphasizing BCT's role in data integrity, trust, and operational efficiency while highlighting untapped opportunities in food traceability and sustainable SC management.	RQ1 and RQ2
4	United Kingdom	2024	Jellason, N. P., Ambituuni, A., Adua, D. A., Jellason, J. A., Muhammad, I. Q., Olarinde, A., & Manning, L.	Beef, baby food, grain, rice, organic food, coffee, coca, dairy, olive, wine, pork, halal poultry, fish, wheat, avocado, tea, eggs, milk, nuts	Qualitative	A systematic review of BCT's impact on small-scale agri-food businesses, focusing on its role in enhancing SC resilience and the challenges of implementation.	BCT can strengthen SC resilience for small-scale agri-food businesses by enhancing traceability, transparency, and trust while mitigating food fraud and product loss. However, challenges like data disclosure concerns, costs, and lack of trust must be addressed for successful adoption.	RQ1 and RQ2
5	Italy	2024	Maritano, V., Barge, P., Biglia, A., Comba, L., Ricauda Aimonino, D., Tortia, C., & Gay, P.	Dairy, meat, fish and seafood, wine and spirits	Conceptual	An updated analysis of anti-counterfeiting technologies in the most fraud-prone FSCs: dairy, meat, fish & seafood, and alcoholic drinks, assessing their adoption and potential for enhancing food safety and brand protection.	Electronic and data-driven technologies like RFID and digital traceability are still in early adoption in fraud-prone food sectors. Integrating multiple anti-counterfeiting technologies offers stronger protection than single solutions, but companies should prioritize those with the highest benefit-cost ratio.	RQ 1
6	Greece	2024	Melissari, F., Papadakis, A., Chatzitheodorou, D., Tran, D., Schouteten, J., Athanasiou, G., & Zahariadis, T.	Dairy, meat, fish and seafood, wine and spirits	Quantitative	Explores the feasibility of using BCT to model PDO feta cheese production rules for a reliable traceability system. It aims to link operational data with consumer-relevant product traits, design an accessible system with minimal BC delays, and provide consumer verification tools via BC access.	BCT can establish a reliable traceability system for feta cheese by modeling production, codifying rules into smart contracts, and using dual-chain architecture for scalability and public verification. Consumers can verify data integrity and compliance via an online platform and public BC access.	RQ1
7	Colombia	2024	Garzón, W. A. O., Sandoval-Aldana, A., & Arteaga, J. J. M.	Agri-food	Qualitative	A systematic literature review identifying barriers and enablers to implementing food informatics technologies in agri-food. It explores common factors influencing adoption from a global supply chain perspective.	A review identified 34 barriers and 27 enablers to implementing food informatics in agri-food chains. Key barriers include data privacy, security, and high costs, while government support is a major enabler. Adoption is shaped by technological, social, economic, organizational, and institutional factors. Future research should develop a computational model to analyze their interdependencies.	RQ2
8	India	2024	Panigrahi, A., Pati, A., Dash, B., Sahoo, G., Singha, D., & Das, M.	Fish, wine, fruit, pork	Conceptual	Examines BC's role in agriculture-based SCM and develops ABSlock, a BC-based decentralized application. Performance is evaluated through gas utilization and latency in key generation and validation.	BCT improves reliability and transparency in agricultural SCs. The proposed dApp enables secure communication and transactions among farmers, retailers, and consumers. The developed ABSlock dApp has an average gas utilization of ~2.8*10^^ and a smart contract execution time of ~112 seconds.	RQ1

9	Africa	2024	Tang, A., Tchao, E. T., Agbemenu, A. S., Keelson, E., Klogo, G. S., & Kponyo, J. J.	Olive oil, fish, palm oil, cocoa, wine, rice, vegetables, fruit, fair-trade, dairy, seafood, beef	Qualitative	A systematic analysis of BC and IoT feasibility in enhancing traceability and integrity in African agricultural FSCs. It highlights their potential and adoption challenges, including scalability, costs, and regulatory compliance."	BC and IoT can improve food traceability and combat fraud in African agricultural SCs, but challenges like scalability, costs, and regulatory compliance must be addressed. A context-sensitive approach is essential, considering diverse socio-economic and infrastructural conditions, requiring collaboration among governments, industry, and technology providers.	RQ1 and RQ2
10	Greece	2024	Vitaskos, V., Demestichas, K., Karetsos, S., & Costopoulou, C.	Olive oil	Qualitative	Proposes a BC-based traceability system for the olive oil SC, integrating IoT to enhance transparency, ensure quality, and prevent fraud. It examines vulnerabilities and assesses the system's effectiveness in addressing them.	The proposed BC-IoT system improves transparency and traceability in the olive oil SC. Survey results highlight its effectiveness in boosting consumer trust and ensuring authenticity. Key features include smart contracts and real-time monitoring, enabling automated quality checks, fraud reduction, and scalability for other high-value agricultural products.	RQ1 and RQ2
11	Italy	2024	Zarbà, C., Chinnici, G., Matarazzo, A., Privitera, D., & Scuderi, A.	Agri-good	Quantitative	Explores BCT's role in supporting the agri-food system by enhancing transparency and traceability. It examines BC's perceived value across gari FSC stages, identifying challenges, performance benefits, and practical requirements for effective implementation in the food industry.	Interest in BCT is growing in the agri-food sector for its potential to enhance traceability and transparency through decentralized data management. It can improve food safety, boost consumer trust, and create a more efficient SC by reducing information asymmetry and ensuring immutable records. However, challenges in implementation and governance remain.	RQ 1
12	Italy	2023	Bandinelli, R., Scozzafava, G., Bindi, B., & Fani, V.	Ancient wheat	Qualitative	A survey of 366 Italian respondents assesses consumer reactions to ancient wheat pasta packaging with BCT-based origin and processing details. It also identifies key factors influencing consumer adoption of BCT in this SC.	Consumers are interested in BCT for food tracking, especially if it ensures security and quality. They are willing to pay more for BC-verified products, emphasizing the role of perceived security and trust in adoption.	RQ1 and RQ2
13	Australia	2023	Chandan, A., John, M., & Potdar, V.	Agri-food, processed or packaged foods, perishable goods, extra virgin plive oil, grain, cocoa beans, fish, meat, honey, organic food	Qualitative	An SLR examining BCT's role in addressing FSC sustainability challenges to achieve UN SDGs. It identifies key issues, explores VC features as solutions, and analyzes interactions between challenges, BC applications, and SDGs.	BCT enhances FSC sustainability by improving transparency, traceability, accountability, and financial efficiency, supporting UN SDGs. However, its adoption is still in early stages, facing challenges like high costs, limited technical expertise, and the need for global policies and standards.	RQ 2
14	India	2023	Goyal, A., Kanyal, H. S., & Sharma, B.	Agri-food	Conceptual	A review of BC and IoT applications in agricultural FSC transactions, focusing on their role in enhancing productivity, transparency, and traceability in agricultural insurance, smart farming, and FSCM.	Integrating BC and IoT enhances agricultural FSC transactions by improving traceability, transparency, and security. These technologies streamline processes, reduce fraud, and build trust among stakeholders, including farmers and consumers.	RQ1 and RQ2
15	France	2023	Hassoun, A., Kamiloglu, S., Garcia-Garcia, G., Parra-López, C., Trollman, H., Jagtap, S., Aadil, R. M., & Esatbeyoglu, T.	Fruit and vegetable	Conceptual	A review of recent advances in Traceability 4.0 for the fruit and vegetable sector, highlighting Industry 4.0 technologies: AI, IoT, blockchain, and big data to improve quality, safety, transparency, and reduce recall costs, waste, and loss.	Traceability 4.0 technologies can enhance fruit and vegetable quality, safety, and SC transparency while reducing recall costs, waste, and loss. However, adoption remains limited due to high costs and poor industrial adaptability, with most applications still at the lab stage.	RQ 2
16	Montenegro	2023	Malisic, B., Misic, N., Krco, S., Martinovic, A., Tinaj, S., & Popovic, T.	Wine and olive oil	Qualitative	An SLR identifying BC's value proposition, competitive advantages, adoption challenges, key players in authentication and value chain recording, and its main applications in the wine sector.	BCT benefits the wine industry by enhancing traceability, ensuring data immutability, and building stakeholder trust. However, adoption faces challenges like high costs, skill gaps, and the need for standardized regulations and protocols.	RQ1 and RQ2
17	Australia	2023	Mohammed, A., Potdar, V., Quaddus, M., & Hui, W.	Dairy, eggs, meat, mangoes, Halal food, olive oil, grains, rice	Conceptual	Develops an integrated framework for BCT adoption in FSC, identifying and synthesizing its enablers, benefits, and barriers.	BCT can transform FSC by enhancing traceability, transparency, and efficiency. However, challenges like scalability, interoperability, high costs, skill gaps, and regulatory issues must be addressed for successful adoption.	RQ1 and RQ2
18	China	2023	Zheng, Y., Xu, Y., & Qiu, Z.	Rice, milk, livestock, vegetables, fruit, soybeans, fresh food, olive oil	Quantitative	Uses mathematical modeling and simulations to analyze long-term decision-making in agricultural SCs for BC traceability adoption. It identifies key influence factors and determines evolutionary stable strategies (ESS) across different scenarios.	Government agencies drive BC traceability in agricultural SCs through regulations, incentives, and penalties. Adoption follows three stages as producers and processors overcome initial hesitancy. Subsidies are more effective than penalties in encouraging adoption.	RQ1 and RQ2
19	Austria	2022	Treiblmaier, H., & Garaus, M.	Honey and salmon	Quantative	An experimental study on how BCT-based traceability labels influence consumer perceptions of product quality and purchase intention, with a focus on brand familiarity as a moderating factor.	BC-based traceability labels enhance consumer perceptions of product quality, boosting purchase intentions. However, this effect is stronger for less familiar brands, while familiar brands see little impact.	RQ1 and RQ2
20	France	2022	Alkhudary, R., Brusset, X., Naseraldin, H., & Féniès, P.	Olive Oil	Conceptual	A theoretical framework for an olive oil SC using BC, IoT, and smart contracts to enhance transparency and prevent fraud. The system offers a competitive advantage and ensures product authenticity across production stages.	BCT, IoT, and smart contracts enhance visibility and fraud prevention in the OOSC. The system enables transparent quality data sharing among partners, eliminating the need for third-party regulators."	RQ1 and RQ2
21	Belgium	2022	Bager, S., Singh, C., & Persson, U. M.	Coffee	Qualitative	A case study evaluating BCT's potential to enhance sustainability in the coffee SC by improving traceability and transparency. It examines adoption barriers, opportunities, and the impact of value chain characteristics on implementation and operability.	BCT enhances traceability and information flow in the coffee SC but faces challenges like product mixing, infrastructure needs, and data validity. While not a standalone solution for sustainability, its true value lies in digitizing the SC for greater efficiency, cost reduction, and improved product provenance.	RQ 1
22	Serbia	2022	Guruswamy, S., Pojić, M., Subramanian, J., Mastilović, J., Sarang, S., Subbanagounder, A., & Jeoti, V.	Staple commodities and high-value commodities	Conceptual	Reviews Industry 5.0 technologies' role in enhancing FSC from production to retail, focusing on sustainability, quality, integrity, and security. It explores how big data, AI, IoE, digital twins, blockchain, cobots, and 6G can strengthen food security and resilience, especially during crises.	Industry 5.0 technologies enhance food security and sustainability by digitizing and optimizing FSCs. Integrating AI, big data, blockchain, and digital twins improves traceability, reduces waste, strengthens resilience, and fosters human-machine collaboration.	RQ1 and RQ2
23	The Nederlands	2022	Jiménez-Carvelo, A. M., Li, P., Erasmus, S. W., Wang, H., & van Ruth, S. M.	Wine, Chinese red dates, meat, beverage	Conceptual	Explores spatial-temporal data analysis in FSC for early food fraud detection. It examines how patterns in scanned product IDs, like QR codes, can reveal anomalies indicating fraud.	Spatial-temporal analysis of scanned product IDs is a powerful early warning tool for detecting food fraud in SCs. By analyzing scan patterns, it can identify anomalies linked to counterfeiting, theft, or fraud. Combined with ML, it enhances anomaly detection in SCs.	RQ 1
24	United States	2022	Khan, S. A.	Not specified	Conceptual	Explores 'food stories' in complex food systems and technological interventions like BC and digital twins. It examines how, while aimed at transparency and quality, they can be leveraged for corporate control and fail to address systemic issues.	Food stories, enabled by BC, are not neutral tools for transparency but can reinforce corporate power and obscure systemic inequalities. While promising transparency and control, these technologies mirror the complexities of global SCs, exposing their unpredictability rather than providing clear solutions.	RQ1 and RQ2
25	India	2022	Khanna, A., Jain, S., Burgio, A., Bolshev, V., & Panchenko, V.	Dairy	Qualitative	An SLR proposing a BC-enabled SC platform for India's dairy industry to combat food fraud, contamination, and adulteration. Beyond traceability, it aims to preserve nutritional values, detect adulteration, and boost dairy company revenue.	A BC-enabled SC platform can enhance food safety, traceability, and transparency in India's dairy industry. Integrating smart contracts, QR codes, and IoT, it fosters a decentralized, robust, and sustainable SC while tackling adulteration, contamination, and transparency issues.	RQ1 and RQ2
26	Italy	2022	Marchesi, L., Mannaro, K., Marchesi, M., & Tonelli, R.	Agri-food	Quantitative	Develops a semi-automatic, configurable system for BC applications in Agri-FSCM, offering prebuilt code blocks to streamline development, reduce time, and ensure security.	The modular system with flexible data representation provides a scalable approach for BC-based traceability, applicable beyond agri-food to other SCs.	RQ1 and RQ2
27	United Arabic Emirates	2022	Patro, P. K., Jayaraman, R., Salah, K., & Yaqoob, I.	Fish	conceptual and quanitative	Proposes a BC-based solution on a private Ethereum network to tackle food fraud, traceability, and data management in the fish SC. The system ensures secure, transparent tracking of wild-caught and farmed fish, using smart contracts for automation and accountability.	The tested and validated system, using Remix IDE, offers a secure, transparent, and accountable method for tracking fish products, addressing food fraud and data management challenges.	RQ1 and RQ2
28	India	2022	Singh, V., & Sharma, S. K.	Not specified	Conceptual and qualitative	A review, expert interviews, and case study analysis explore BCT's potential to enhance consumer confidence in the food industry by improving traceability and combating food fraud. It examines how BC empowers consumers to verify product claims and promotes transparency across the FSC.	BCT enhances FSC transparency and traceability, strengthening consumer trust and reducing food fraud. Its secure, immutable records enable consumers to verify product claims, fostering a more accountable food industry.	RQ1 and RQ2

29	Italy	2021	Adamashvili, N., State, R., Tricase, C., & Fiore, M.	Wine	Qualitative	A case study on BCT's characteristics and impact on industries, particularly SCs. It compares traditional and BCT-based SCs in information sharing, tracking time, costs, and reducing disorganization. Using a wine SC model, it demonstrates BCT's role in enhancing traceability and preventing fraud.	BCT reduces recall times for low-quality products compared to traditional SCs. Its transparency and immutability reduce disorganization and inefficiencies.	RQ1 and RQ2
30	Austria	2021	Garaus, M., & Treiblmaier, h.	Not specified	Qualitative	An experimental study examining how BCT-based food traceability affects consumer trust and retailer choice.	BC-based traceability boosts consumer trust, positively influencing retailer choice, especially for unfamiliar retailers and when BC benefits are highlighted.	RQ 1
31	Denamrk	2021	Katsikouli, P., Wilde, A. S., Dragoni, N., & Jensen, H. H.	Coffee, smoked salmon, vegan/vegetarian food, organic, flavors	Qualitative	A Danish food industry case study on SMEs exploring BCT and distributed ledger adoption in FSC management. It examines benefits, challenges, and limitations, focusing on food safety, fraud, inefficiencies, fair trade, animal welfare, and environmental impact.	BCT enhances FSCM by improving traceability, transparency, and efficiency while tackling food fraud and promoting fair trade and sustainability. However, adoption is hindered by limited understanding, lack of standardization, interoperability, and the need for policies and regulations.	RQ1 and RQ2
32	Italy	2021	Mercuri, F., della Corte, G., & Ricci, F.	Not specified	Qualitative	A case study on Devoleum exploring how BCT supports and promotes sustainability in business models.	BCT enhances sustainability by enabling traceability, security, and data integrity, especially in agri-food. By reducing intermediaries, it lowers transaction costs and strengthens business relationships, fostering sustainable models.	RQ 1
33	Indonesia	2021	Sidarto, L. P., & Hamka, A.	Halal (poultry)	Qualitative	A case study on BCT's role in improving Halal traceability in the poultry industry. It examines gaps in current Halal labeling and demonstrates BC-based system implementation in a poultry company.	A BC-based traceability system improves transparency and integrity in Halal labeling by providing stakeholders with end-to-end data access. While promising for monitoring, further research is needed to evaluate its long-term impact on consumer trust and SC efficiency.	RQ1
34	Italy	2020	Stranieri, S., Riccardi, F., Meuwissen, M. P. M., & Soregaroli, C.	Poultry meat, lemons, and oranges	Qualitative	A case study evaluating BCT's impact on FSC performance through an integrated framework covering efficiency, flexibility, responsiveness, food quality, and transparency. It also examines SC transaction reorganization and changes in firm resources and capabilities.	BCT enhances SC performance by boosting profits, ROI, and extrinsic food quality while improving information management through better accessibility, availability, and sharing. It also drives SC transaction reorganization, strengthening collaboration and firm capabilities.	RQ1 and RQ2
35	United Kingdom	2020	Rogerson, M., & Parry, G.	Fish, wine, and infant formula	Qualitative	Qualitative analysis using semi-structured interviews to examine BCT's role in enhancing SC visibility and trust in the food industry, while identifying its challenges and limitations	BC enhances SC visibility by ensuring reliable data and provenance, especially in fully digitized systems. However, challenges like trust, human error, governance, and consumer data access remain.	RQ1 and RQ2
36	China	2018	Mao, D., Wang, F., Hao, Z., & Li, H.	Not specified	Quantitative	Proposes a BC-based credit evaluation system for FSC to tackle information asymmetry and stakeholder supervision challenges. Using smart contracts, it collects trader credit evaluations, analyzed via a long short-term memory deep learning network, providing regulators with reliable oversight.	The system mitigates information asymmetry by offering a transparent, accountable platform for regulators, outperforming traditional methods like SVM and NB in credit evaluation text analysis.	RQ 2