

Review

# Distributed Ledger Technology Applications in Food Supply Chains: A Review of Challenges and Future Research Directions

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**Citation:** Nurgazina, J.; Pakdeetrakulwong, U.; Moser, T.; Reiner G. Distributed Ledger Technology Applications in Food Supply Chains: A Review of Challenges and Future Research Directions. *Sustainability* **2021**, *13*, 4206. <https://doi.org/10.3390/su13084206>

Academic Editor: Caterina Tricase, Angela Tarabella and Pasquale Giungato

Received: 14 March 2021

Accepted: 8 April 2021

Published: 9 April 2021

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**Abstract:** The lack of transparency and traceability in food supply chains (FSCs) is raising concerns among consumers and stakeholders about food information credibility, food quality, and safety. Insufficient records, a lack of digitalization and standardization of processes, and information exchange are some of the most critical challenges, which can be tackled with disruptive technologies, such as the Internet of Things (IoT), blockchain, and distributed ledger technologies (DLTs). Studies provide evidence that novel technological and sustainable practices in FSCs are necessary. This paper aims to describe current practical applications of DLTs and IoT in FSCs, investigating the challenges of implementation, and potentials for future research directions, thus contributing to achievement of the United Nations' Sustainable Development Goals (SDGs). Within a systematic literature review, the content of 69 academic publications was analyzed, describing aspects of implementation and measures to address the challenges of scalability, security, and privacy of DLT, and IoT solutions. The challenges of high costs, standardization, regulation, interoperability, and energy consumption of DLT solutions were also classified as highly relevant, but were not widely addressed in literature. The application of DLTs in FSCs can potentially contribute to 6 strategic SDGs, providing synergies and possibilities for more sustainable, traceable, and transparent FSCs.

**Keywords:** distributed ledger technology; Internet of Things; food supply chain; blockchain; sustainability; IoT; review

## 1. Introduction

Food path traceability and food information credibility are the critical aspects in agricultural and food supply chains (FSCs) [1–5]. Complex supply chain networks are comprised of numerous intermediaries, who are often reluctant to share traceability information [4], contributing to a lack of transparency, digitalization, and supporting systems [1]. Various risk factors can influence food quality and safety, such as various hazardous compounds included in stages of packaging, production, processing, or storage, which can impose serious health risks to consumers [6]. Product quality at each stage in the supply chain depends on the quality of the prior stages and hence the quality of the final product depends on the proper traceability practices across the entire supply chain [5,6]. Implementation of automatic systems for data capture are costly and diversity of the systems makes it hard to implement them in practice [2,3]. However, food trade globalization [3] forces stakeholders in supply chains, e.g., farmers, manufacturers, retailers, and distributors, to adopt traceability standards [2,4], which imposes even more

difficulties for small-scale producers and farmers [1]. This brings another critical challenge in terms of standardization of processes, data, and information exchange among stakeholders in supply chains [2–4], as well as digitalization barriers. A lack of digitalization leads to processes and paperwork done manually resulting in human error [7], a lack of available records, slow-tracing, and difficulties in retrieving information and sorting products [1]. Food scandals, food fraud [4,7], and food contamination incidents [1–3] lead to rising concerns regarding food quality, safety, and information credibility among consumers and stakeholders [1–3]. Hence, the implementation of digital technologies is becoming a necessity and a competitive advantage [8,9] to sustain operations in the market, to decrease various supply chain risks [1,2,7], and to regain public confidence in food safety, food security, and quality [3,7,9,10]. There is a rising trend of digitalization in the food industry and FSCs with integration of technologies, such as the Internet of Things (IoT), blockchain, and distributed ledger technologies (DLTs) [8,10]. In particular, there is an increased need of system management solutions for IoT-integrated blockchain systems for transparency, security, and traceability of FSCs [1,2,4,7,10].

Sensor technologies, such as IoT and cyber-physical systems (CPS) have been widely integrated in FSCs to preserve logistics monitoring, product quality tracking and process control [1,11], and to ensure data-driven decision making [12]. Sensors capture and store critical food data, such as food conditions, location history, and product life cycle, thereby improving storage management, stockpiling and allocation prioritization, thus preventing product losses, contamination, and spoilage [1,2,11,12]. Various sensor technologies, such as the global positioning system (GPS), geographic information system (GIS), near-field communication (NFC), radio frequency identification (RFID), and temperature and humidity sensors, can improve monitoring and information capturing in various processes [13], such as production, processing, storage, distribution, and retail [1,11]. However, there are several challenges of IoT deployments, such as cyber-security and safety risks [1,8,13], data confidentiality [4], vulnerability, and data integrity [13]. Integration of blockchain technology in IoT systems can potentially improve system security and address such challenges [1,8,13]. For instance, blockchains can help prevent food fraud by retaining trustworthy product information on biological and geographic origin [1,2]. Additionally, blockchains can benefit production planning and scheduling across supply chains [14]. The combination of blockchains with IoT can potentially improve FSCs transparency, efficiency, and sustainability [5,13] save costs and time [2,8,13], reduce information asymmetry, paperwork, fraud risks, and increase trust among supply chain stakeholders and end consumers [5,13].

DLT is a term used to represent a digital network of distributed models, consisting of blockchain-based ledgers, and collaborating on shared tasks and activities. Blockchain technology is a data structure, composed of “blocks”, that are cryptographically linked together in a chained sequence using cryptographic hashes, secured against manipulations [11,15]. Due to wider functionality, DLT is a commonly used term for a computer-based system consisting of distributed ledger-based data structures, which can provide increased levels of trust, service availability, resiliency, and security of digital systems, as well as distributed storage, computation, and control [15].

The 2030 Agenda for Sustainable Development Goals (SDGs) of the United Nations (UN) [16] provides solid and important guidelines, with several of them directly affected by traceability of FSCs: good health and wellbeing (SDG 3) [17,18], decent work and economic growth (SDG 8) [17–19], industry and infrastructure (SDG 9), clean water and sanitation (SDG 6) [10], sustainable cities and communities (SDG 11), and responsible consumption and production (SDG 12) [17,18], which need to be addressed on governmental, organizational and personal levels across societies [12,16,19].

Integration of DLTs across organizations and infrastructures can enhance stability, resilience, and security of systems [8,15], enabling distributed solutions for industries and societies. Fostering sustainable innovation, digitalization, and industrialization can

potentially contribute to the SDG 9. Real-time and reliable product-related information, such as temperature, humidity, light or chemical conditions [2,6], shared across FSCs, can prevent or predict food contamination, food waste, and food spoilage issues [2,6], additionally providing automation of processes, such as shelf-life management and product recall [13], tracking of expiry dates, thereby contributing to SDGs 3 and 12. Food fraud [1,2,4], a lack of transparency [12], trust issues [20,21], and various ethical and labor issues in FSCs can be addressed with digitized data and information exchange among stakeholders in FSCs [12,20,21], decreasing the roles of middlemen [21]. Digitalization practices in agriculture and food production processes with DLTs, IoT, and other emerging technologies, such as artificial intelligence (AI), cloud- and fog computing, and big data analytics, can additionally contribute to the reduction of food waste, inefficient use of resources, and data-driven decision-making in FSCs [12,19], contributing to SDGs 6 and 11. Aspects addressing sustainability and improving the quality of life with the blockchain have been pointed out, specifically for education, environment, health, local economy, social inclusion, and improved waste management [17], as well as sustainable water management [10].

Despite the potentials of DLT implementation in FSCs with improved security, provenance, reliability, visibility, and neutrality in supply chain operations [7,9], application and development of DLTs in supply chains is still in its early stages [8,13]. The lack of uniform technology standards and regulations [3,10,22], insufficient data, traceability processes, interface standardization [4], the lack of technology understanding [3,10,22], and digitalization barriers are some of the obstacles that hinder widespread adoption [3,10,22]. There have been initiatives addressing current barriers and applications of blockchain implementation in supply chains [7,8,10], addressing benefits and challenges of adoption in FSCs [3,7,22], with content-based analysis [13] and suggestions for future research directions [10] for improved sustainability of FSCs [13,17,22]. In recent publications, the challenges of scalability, security, and privacy of DLT and IoT solutions were highlighted as some of the most critical in ongoing research [10,22–26]. This systematic literature review (SLR) paper provides content-based detailed analysis and systematic review of papers, addressing technical details of DLT and IoT implementation in FSCs with the following contributions and objectives:

- The challenges of scalability, security, and privacy and practices to address them are described in detail.
- Suggestions for future research directions are provided, with wider interpretation of their relevance to the SDGs [17] and contribution towards more transparent, traceable, and sustainable FSCs.

Based on the highlighted research objectives, the following research questions (RQs) were be addressed in this study:

RQ 1: What challenges of DLT and IoT implementation in FSCs were identified and how were they addressed in literature?

RQ 2: What implications for future research directions were elaborated and how can they contribute to the SDGs?

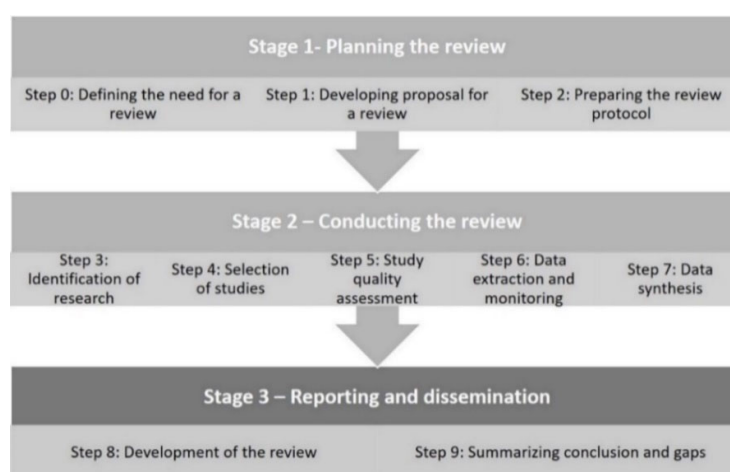
The remainder of this SLR paper is structured as follows: Section 2 describes the research methodology of the SLR. Section 3 discusses the main findings, provides an overview and summary of analyzed papers, and presents classification of challenges of DLT and IoT implementation into eight thematic clusters. Section 4 discusses the implications for future research directions and their relevance to the SDGs. Section 5 discusses the major findings. Section 6 describes the limitations of the study and summarizes the key findings and contributions of the SLR.

## 2. Research Methodology

This SLR follows the approach of Tranfield et al. [27], modified and adapted from the approaches of Queiroz et al. [8] and Roberta Pereira et al. [28].

To address the research questions, we performed a SLR approach, presented in Figure 1. During the stages of the SLR, summary of existing academic literature was carried out, including current issues and trends, assessing scientific contributions, based on and opposed to the current and existing knowledge [29].

In Stage 1 of the SLR, the target research topic was identified, defining applications of DLT and IoT in FSCs domain. At this stage, a research protocol was developed, and search keywords were selected. Search queries were performed in five databases: IEEE Xplore Digital Library, ScienceDirect, Springer Link, Taylor and Francis Online, and Wiley Online Library. The combination of the following keywords was used in the search: “blockchain” OR “distributed ledger” AND “food supply chain”. In the search, no duplicates were detected. The details of the research protocol are summarized in Table 1. Based on the keywords and selection criteria used, publications made available online until (and including) December 2020 were selected in the process.



**Figure 1.** Systematic literature review (SLR) approach adapted from [8,27].

The publications, which included the description of DLT and IoT implementation details in FSCs were considered and summarized in this review. The identified publications were screened for validity based on selection criteria, which is specified in the research protocol and outlined in Table 1.

**Table 1.** Research protocol based on [8,28,30]

Research Protocol	Details
Search in databases	Search queries performed in the following databases: IEEE Xplore Digital Library (IEEE) <sup>1</sup> , ScienceDirect <sup>2</sup> , Springer Link <sup>3</sup> , Taylor and Francis Online <sup>4</sup> , and Wiley Online Library <sup>5</sup> . No duplicates were detected
Publication type	Peer-reviewed papers
Language	All publications in English language
Date range	All time span until (including) December 2020
Search fields	Abstract (IEEE); title, terms, abstract, keywords (ScienceDirect); and full text search (Springer, Taylor and Francis, Wiley)
Search terms	“blockchain” OR “distributed ledger” AND “food supply chain”
Inclusion criteria	Only papers describing relevant blockchain or distributed ledger technologies (DLTs) and IoT (also: sensors, traceability) application in food supply chain (FSC) were included

Exclusion criteria	Papers in other domains (e.g., wind energy, healthcare) and papers not presenting research or implementation details were omitted. Repetitive or irrelevant content was omitted
Data extraction and monitoring	Papers were screened for validity: describing blockchain or DLT implementation or research. Book chapters, magazines, conference and journal publications were considered
Data analysis and synthesis	Shortlisted papers were read through and analyzed, covering current practices of blockchain or DLT and IoT implementation and research in FSCs domain

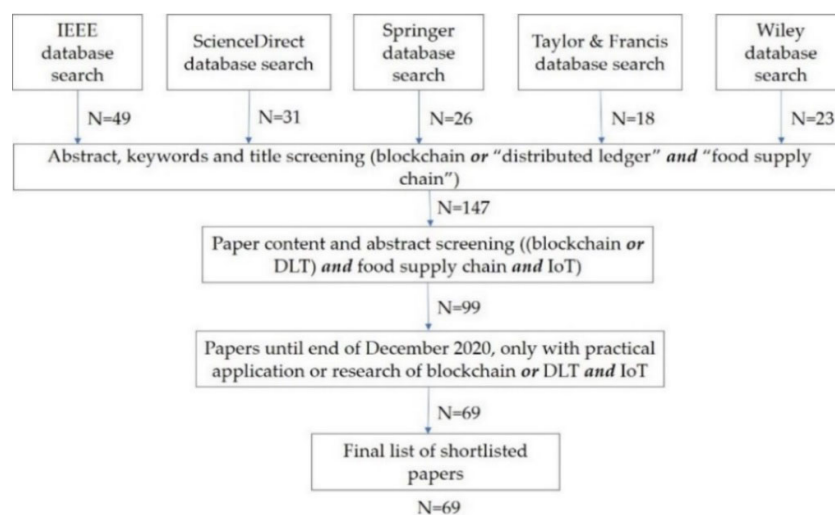
<sup>1</sup> IEEE Xplore: <https://ieeexplore.ieee.org/search/>; <sup>2</sup> ScienceDirect:

<https://www.sciencedirect.com/search/>; <sup>3</sup> Springer Link: <https://link.springer.com/>; <sup>4</sup> Taylor and

Francis: <https://www.tandfonline.com/>; <sup>5</sup> Wiley Online Library: <https://onlinelibrary.wiley.com/> (accessed on 29.01.2021).

In Stage 2, the search terms were selected to shortlist the initial number of publications. Based on identified selection criteria, papers not satisfying the criteria were omitted, e.g., papers in other application domains, such as healthcare, wind energy, etc., or papers not describing implementation or research details of DLT, blockchain, and IoT implementation in FSCs. The search fields were defined differently in different databases, as described in Table 1. After each selection stage, the selected papers were counted and documented in a common spreadsheet during the selection process, adapted from [24], presented in Figure 2. Out of 147 originally found papers, 69 publications were subsequently shortlisted for detailed analysis, among which 25 were conference papers, 40 were journal publications, and 4 book sections, which resulted in a selection rate of 46.94%.

In Stage 3 of the SLR, the main review findings were elaborated, visualizations were developed, and research questions were finalized and addressed. At this stage, challenges of blockchain, DLT and IoT applications were identified from selected literature, summarized, and classified into eight thematic clusters. Based on the findings, future research directions and their relevance for the SDGs were elaborated. Additionally, the papers were classified based on the research methods used, food domain and publication type, presented in Section 3.



**Figure 2.** SLR process adapted from [28]

Throughout the SLR process, key findings, implementation details, and challenges were summarized.

### 3. Results and Discussion

In this section, the classification of selected research papers is presented. The challenges of scalability, security, and privacy were classified as the most relevant and occurring in the analyzed literature [10,22–26,31], along with other highlighted challenges. In this section, the current challenges of DLT and IoT implementation in the food sector are summarized, and the top three classified challenges of scalability, security, and privacy are described in detail. The shortlisted publications mostly covered the experimental stage of development, i.e., proposing a system, a framework design, or a prototype, while only 15 out of 69 publications were case studies, 23 were review papers, and 6 (out of 69) were quantitative simulation-based studies. There were publications, which applied to more than one research method as well.

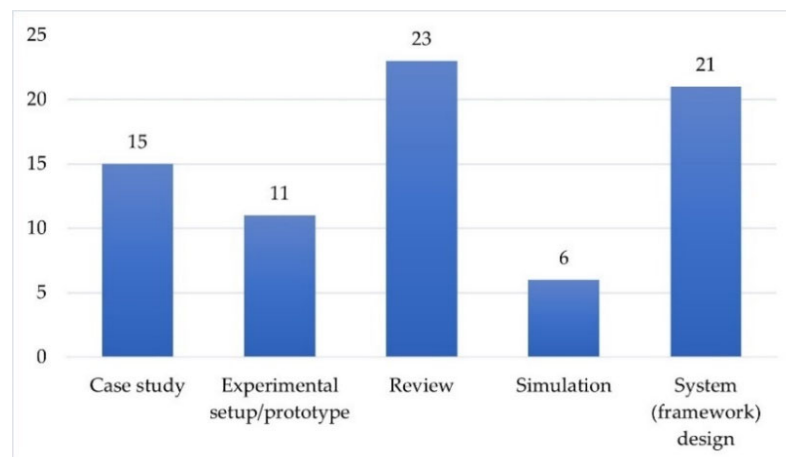
#### 3.1. Classification of Selected Research Papers

For this SLR, the shortlisted 69 research papers were classified into several criteria: research methods, food domain, and publication type. Using the adapted approach from [32], the papers were classified into five research methods, depicted in Figure 3.

For the classified papers, only papers describing implementation details of blockchain, DLT, and IoT in FSCs were included in the review, including theoretical review papers. The identified research methods in the selected literature are:

1. Review.
2. System (framework) design.
3. Experimental setup/prototype.
4. Case study.
5. Simulation.

The classification of papers was carried out according to authors' understanding and interpretation of findings, considering relevance and technological contribution of the analyzed publications. The validation of the classifications to research methods was performed by two authors to cross-check the validity of the identified research methods, and to prevent possible bias in allocation. If a publication included more than one research method, both research methods were added into the classification as separate methods. The summary of shortlisted papers, based on the application domain, publication type, publication year, and research method are depicted in Table A1 in Appendix A.



**Figure 3.** Research methods of shortlisted papers.

In our classification, the case study stage includes and assumes the previous stages of experimental setup (prototype) or the system (framework) design were implemented, and a final solution was evaluated in a company setting. Various review papers addressed

DLT implementation challenges, providing summary of areas of application, potentials, and suggestions for further research directions in food and agri-food [1,12,19,21,25,33–41], agriculture and precision agriculture [24,26,31,42–44], and seafood [45] domains.

### 3.2. Challenges of DLT and IoT Implementation in FSCs

To identify the most frequent keywords and to visualize a data set of identified challenges, the software of ATLAS.ti was used. The identified challenges were summarized in a spreadsheet file, which was uploaded into the software for further analysis. In total, 196 keywords related to challenges were identified from the selected literature.

Among the challenges identified, the most prominent and frequent occurrences were the challenges of scalability, security, cost, privacy, storage, energy consumption, latency, and interoperability. Considering the previous studies [23–25], we provide a comprehensive description of the scalability, security, and privacy challenges, as well as the measures to address them, as presented in literature. The 15 most occurring keywords of challenges, with at least 5 occurrences, are depicted in Table 2.

**Table 2.** Top 15 most frequent keywords (challenges).

Ranking	Challenge	Count (Frequency)
1	Scalability	25
2	Security	22
3	Privacy	20
4	Cost	19
5	Interoperability	18
6	Energy consumption	13
7	Latency	12
8	Storage	12
9	Standardization	10
10	Regulations	8
11	Stakeholder involvement	8
12	Confidentiality	7
13	Digitalization	7
14	Technology immaturity	6
15	Data integrity	5

#### 3.2.1. Scalability Challenges

The most frequent and prominent challenge, which was identified in the selected literature, was the scalability issue of blockchain and IoT implementation in FSCs, i.e., the ability to maintain transactions of a network at scale without business process interruption [41]. The consensus algorithms of blockchains, such as Proof-of-Work and Proof-of-Stake, require competition for computational resources, hence achieving scalability and stability in blockchain and IoT-based systems is still a challenge [46].

Current existing blockchain platforms, such as Hyperledger Sawtooth, are not capable to handle high amount of data arriving simultaneously, including sensory data and IoT data, due to the low maturity of the solution. [47] highlighted the scalability issue of Hyperledger Sawtooth and suggested to dedicate research efforts towards improvement of blockchain scalability [47]. Another solution of the Hyperledger Fabric Composer was investigated by [48], who implemented an experimental study with RFID and IoT for traceability of a halal FSC.

Another blockchain platform, Ethereum, was compared with Hyperledger Sawtooth with respect to performance by [49]. They presented a fully decentralized IoT-integrated blockchain-based traceability solution for agri-food supply chains. From a performance

perspective, the Hyperledger Sawtooth performed better than Ethereum with respect to CPU load, latency, and network traffic. Ethereum had better scalability performance and reliability with increased number of participants, as well as better software maturity [49].

Another way to address the scalability issue of blockchains was the implementation of various mechanisms, one of which being the “sharding” mechanism integrated by [50]. They introduced a permissioned 3-tier blockchain framework, with integrated Hazard Control and Critical Control Point (HACCP), permissioned blockchain, and IoT infrastructure. The “sharding” mechanism used a set of parallel blockchains, called “shards”, to scale the network with large number of transactions in multiple shards in parallel. The task of verifying transactions was divided across multiple shards, and each shard maintained its own synchronized ledger, allocating the shards according to geographic zones. The network performance was evaluated in a simulation, and resulted in a query time of just a few milliseconds even when the data was gathered from multiple shards [41,50] also mentioned the “sharding” mechanism to improve scalability by dividing blockchain data into several nodes or shards, thereby spreading computational power among the nodes simultaneously. In their review, private and consortium blockchain solutions were considered more scalable comparing to public ones, since in public blockchains all nodes share identical responsibilities, e.g., an establishment of a consensus, interaction with user and ledger management [41]. Consortium blockchains are shared among a consortium of multiple institutions, which have access to the blockchain [43]. Private blockchains, on the other hand, allocate tasks to different nodes, which improves performance of the network. Public Ethereum blockchain is able to support 15 transactions per second, while private blockchains, such as Hyperledger Fabric, can provide 3500 transactions per second [41]. Efficient “lightweight” strategies of consensus mechanisms were suggested to address the issues of scalability, data integrity and privacy by performing any expensive high-computational tasks off-chain [41].

Various decentralized storage solutions were investigated to improve the scalability of blockchain solutions. The *Interplanetary File System (IPFS)* and Ethereum blockchain were integrated for decentralized storage of IoT data in an automated FSC traceability model [51], in agri-food prototypical [52], and system design solutions [53,54]. Manufacturer data and various quality inspections details were stored in a centralized server, while IoT data was stored in a so-called table of content (TOC) located both on a central server and on a decentralized database of IPFS. This method allowed a faster transaction process and backward traceability, tracking each product by the TOC identifier from each supply chain member [51]. In addition to the IPFS, different hybrid storage solutions were proposed, including lightweight data structures and a Delegate Proof-of-Stake consensus mechanism, which restricts the number of validators to improve the scalability of the blockchain [24]. Hybrid on-chain and off-chain data storage solutions were described [23,55], such as DoubleChain [24], as well as smart contract filtering algorithms, such as a Distributed Time-based Consensus algorithm, to reduce on-chain data [24]. Additionally, grouping nodes into clusters in the Blockchain of Things infrastructure was suggested to improve blockchain scalability [24].

In [56], a decentralized storage solution for blockchain in the FSC domain was also integrated to enhance throughput, latency, and capacity, introducing the BigchainDB. The real-time IoT sensor data and HACCP were integrated for real-time food tracing. Throughput and latency issues were addressed with the BigchainDB for distributed database, which could increase throughput and data storage in a positive linear correlation, while maintaining blockchain properties, such as immutability, transparency, peer-to-peer network, chronological order of transactions, and decentralized user governance with a consensus mechanism [56].

Moreover, [57] proposed using a lightning network technology with edge computing in a blockchain-based food safety management system to improve transaction and performance efficiency. Real-time transactions were carried out in an off-chain channel



without uploading data on to the blockchain. A dynamic programming algorithm was applied to reduce lightning network fees [57].

Another approach was the introduction of a new consensus algorithm, proposed by [46], who addressed the issue of blockchain scalability by integrating IoT, IBM cloud and blockchain in a scalable traceability system. A system prototype was presented with an integrated consensus mechanism, called the proof of supply chain share, as well as fuzzy logic to perform shelf-life management for perishable food traceability. The feasibility of the proposed model was evaluated with a case study in a retail e-commerce sector [46]. A two-level blockchain solution was additionally proposed by [58], who performed a case study-based pilot project, combining a permissionless (public) ledger, shared externally, with a permissioned ledger, available only to licensed stakeholders [58].

The major concern of recent blockchain developments is the technological immaturity [23], and many approaches highlighted the lack of solid scalable blockchain solutions. Most blockchain initiatives stay in a small implementation or proof-of-concept phase through small pilot studies, while large scale implementations and integration to normal operations are usually initiated by companies, and are not widely represented in research publications [19]. Blockchain technology is still perceived by organizations as an emerging technology and an “experimental tool” for achieving a potential competitive advantage in future [19].

### 3.2.2. Security Challenges

There are numerous benefits blockchains can provide, such as enhanced IoT and cloud security [43], reduction of data manipulation [43], anonymity, decentralization, and improved customer satisfaction in terms of security and food safety [6,9,59]. However, there’s a major concern about data security of IoT systems and cyber security of blockchain solutions [34]. A lack of interoperability in regional standards can additionally lead to information asymmetry in supply chains and increased security risks for consumers [60].

To address the security issue [50], an access restriction-based blockchain framework was proposed to keep data about pricing, order details, order frequency, and shipments accessible only for related trading partners. Various client- and network-based attacks and their countermeasures were described, such as double transfer attack, DOS/DDOS attack, wallet theft, sniffing attack, and sybil attack [50]. To ensure automated food quality and safety compliance, an integration with food quality and safety standards, such as ISO 22000, was suggested for implementing smart contracts [61].

The application of asymmetric encryption algorithms [24], such as Ellipse Curve Cryptography, Diffie-Hellman and RSA, and secure protocols, such as Telehash and Whisper, was proposed to enhance data security in a cross-border trade conceptual blockchain system [23].

Another suggestion was a consensus algorithm called proof of supply chain share, proposed by [46], that could mimic the proof of stake algorithm. The hybrid solution comprised of a blockchain, IoT technologies and cloud computing, with minimum data operated on the blockchain to sustain system flexibility and adaptability. To store data efficiently, a mechanism of “blockchain vaporization” was introduced, storing food traceability data, e.g., container ID or batch ID, on the blockchain until the completion of a proof of delivery or point of sales. When the item was sold or delivered, the associated data was “vaporized” from the blockchain and stored only in a cloud database. The IBM cloud solution was integrated to store product data and IoT sensor data [46]. Another solution proposed cloud-based livestock monitoring system with the blockchain and IoT, storing sensor data, such as humidity, movement, and CO<sub>2</sub> emissions, to detect abnormal infection-related behavior [62].

To restrict participant access on the blockchain, [41] described the Proof-of-Authority consensus algorithm with a consortium blockchain solution, approving and determining the number of participants in a trade supply chain. Another consensus algorithm was

introduced by [63], called proof of object. They proposed a new RFID sensor coupled design with a blockchain solution, encrypting terminals with SSL/TLS protocols and implementing extra security features at the hardware level to prevent security attacks [63]. Other efforts analyzed smart contract security and vulnerability of an Ethereum blockchain solution with IPFS in a prototypical implementation. The issues of credibility, authenticity of products, automated payments, and delivery mechanisms in the blockchain were addressed [52]. Other encryption algorithms, such as base-64, were additionally presented [64] to enhance data security.

In [65] proposed a product serialization method to address blockchain security and scalability in a perishable supply chain. Smaller number of transactions on the blockchain could improve the scalability, and a secure serialization protocol was used to verify the authenticity of serial numbers. A path-based fund transfer protocol was proposed to prevent the sale of expired products [65].

Another approach to enhance the DLT security was proposed by [66], who implemented a federated interledger blockchain solution comprising an open-source IoT and DLT platform in a food chain scenario. The interledger blockchain with its combination of private and public blockchains was integrated. Periodical synchronization of a private blockchain ensured data auditability and security. The consortium Ethereum blockchain was integrated among the FSC members. Since there are currently no standards for interconnecting DLT solutions, the benefits of interconnecting multiple ledgers were highlighted [66].

### 3.2.3. Privacy Challenges

The public key infrastructure of DLTs allows to identify users by their public keys, however, especially in the FSC sector, many actors are competitors in the market, which magnifies the issue of stakeholder and user privacy [19].

Hence, to address the privacy issue, [41] described a Peer Blockchain Protocol solution in an e-commerce trading sector, introducing different block types to address trading privacy concerns. Three types of blocks were used in transactions: peer micro-blocks, peer key-blocks and global blocks, pertaining bandwidth requirements, with each block type following different validation strategy [41].

Using multiple ledgers was another technique to improve privacy of blockchain-IoT solutions with a federated interledger approach, i.e., combining several blockchain ledgers [66]. Private and public Ethereum ledgers were integrated, with private ledgers storing participants' confidential data, and public main ledger storing only limited public data. The privacy issues of public blockchains were highlighted, mentioning negative implications of immutability and data replication on user privacy, despite the positive effects of auditability and verifiability [66].

To address the business privacy requirements, various data and information classification techniques were introduced, segregating roles and access rights to shared data [67]. A privacy protection module was integrated in a blockchain prototype, performing user right control and management, generating keys and encrypting private information. A two-way traceability coding scheme was applied to identify and track grain products across a supply chain [67]. Hybrid on-chain and off-chain storage mechanisms, such as DoubleChain [24] were additionally described to preserve data privacy with storing sensitive data off-chain [23,24,55].

Another approach was suggested by [58], who proposed the application of zero knowledge proofs (ZKP) encryption and a permissioned blockchain, providing access only to certified stakeholders and storing limited information on the blockchain. ZKP, or other encryption mechanisms, were proven to ensure identity verification and restricted access to the data, based on pre-defined access rights, thereby enhancing user and business data privacy [58]. Data encryption mechanisms, such as proxy encryption server and improved partial blind signature algorithm, were suggested to ensure data privacy [24]. Additionally, a hierarchical blockchain-based system for improved data privacy and

security was proposed, which ensured chain-to-chain communication, while restricting the number of blocks on the shared chain [24]. A Quorum blockchain platform was described, which is an Ethereum-based platform, that provides transaction data encryption and centralized data control enforcement to preserve data privacy [24].

Despite the initiatives to address the existing issues of blockchain, DLT, and IoT solutions, the privacy and security issues still persist, despite including private or permissioned blockchains and strong encryption mechanisms [38,46]. Moreover, there is a contradiction between concepts of anonymity and decentralization in food traceability systems, especially handling sensitive personal information [46]. More efforts should be dedicated towards improving security and scalability aspects of blockchain, DLT, and IoT solutions, ensuring safe and secure data storage and handling in various business operations [38,46].

### 3.3. Classification of Challenges into Thematic Clusters

The content analysis of shortlisted papers was carried out, identifying 196 keywords of challenges, which were mentioned or addressed in the selected literature. The identified challenges were manually classified into the following thematic clusters: technical and infrastructure, organizational, human, financial, physical, environmental, data-related, and intangibles. The clusters were adapted from [12] classification of supply chain resources, with two additional added categories: environmental and data-related.

The allocation of challenges to each cluster was implemented, considering the authors' perception of their relevance to a particular cluster. The summary of the eight identified clusters and some of their associated keywords are depicted in Table 3. The "Technical and Infrastructure" cluster included the highest number of keywords detected and represented the technical and infrastructure-related issues in DLT and IoT implementation. The second largest cluster was "organizational", including challenges associated with stakeholder, organizational, regulatory, and policy-making issues. The "data-related" cluster included all issues relating to data and information handling, such as data governance, data accessibility and ownership. The "human" cluster considered human-related issues, such as human error or resistance. The "financial" cluster included all financial challenges, and the "physical" cluster included the issues occurring on a physical level, such as sensor tampering. The "environmental" cluster considered the challenges related to sustainability and energy consumption, and the "intangibles" cluster included the issues, such as trust, reputation, and uncertainty.

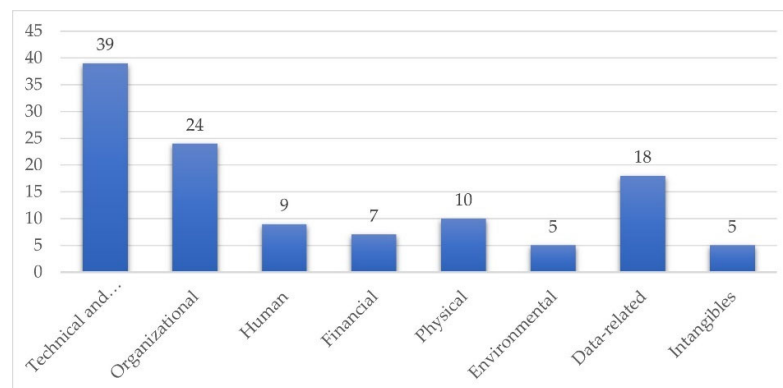
**Table 3.** Classification of identified challenges into 8 thematic clusters.

<b>Technical and Infrastructure</b>	Infrastructure ownership; transaction delay; connectivity; scalability; computational power; security; system integration; storage; interoperability; digitalization (poor infrastructure); privacy; need of automatic control; heterogeneity of solutions; hardware-software complexity; low throughput; insufficient communication protocols; latency; technology immaturity
<b>Organizational</b>	Heterogeneity of actors; confidentiality; participant incompetency; stakeholder involvement; authority issues; policy making; digitalization divide; resistance to openness; new business models; stakeholder governance; source of power; unifying requirements; integrity and honesty; certification; standardization
<b>Human</b>	Training and education; lack of expertise; unclear benefits of blockchains; lack of skills; user society acceptance; cultural adoption; consumer preferences; human error
<b>Financial</b>	Payment mechanisms; economic models; cost and financial investment; financial risks; resource integration; risk factor evaluation

<b>Physical</b>	Connecting pre- and postprocessing information; sensor-tampering; sensor-reliability; bar code tampering; slow-trace; manual work; sensor battery life
<b>Environmental</b>	Sustainability; energy consumption; economic sustainability; energy harvesting
<b>Data-related</b>	Data governance and ownership; key management; data integrity; transparent data management; auditable information sharing; transparency; data accessibility; sensitive data; information connectivity; traceability coding scheme; data redundancy; data incompleteness
<b>Intangibles</b>	Uncertainty; volatility; blockchain-reputation; DLT potential; trust

The number of keywords detected in each cluster is depicted in Figure 4. Previous studies outlined the major challenges related to technical, organizational and regulatory aspects of blockchain implementation in FSCs [22]. In our analysis, a more detailed classification has been elaborated, resulting overall in 8 clusters of challenges.

All clusters and associated keywords are depicted in a mind-map visualization in Figure B1 in Appendix B.



**Figure 4.** Classification of challenges into thematic clusters with numbers of keywords in each cluster.

### 3.4. Summary and Outlook of Challenges and Enablers of DLT Adoption

To achieve FSC traceability practically, further improvements and modifications of existing blockchain, DLT and IoT solutions are needed. The most widespread solutions of Hyperledger Sawtooth [47,49,68], Hyperledger Fabric [48,67,69,70], Ethereum [20,49,51,60,71], Multichain [24], R3 Corda [24], and Quorum [24] were presented in literature with initiatives on new consensus algorithms development, double-chain and interledger approaches [66].

Various initiatives have been implemented to enhance the scalability and security of blockchain, DLT and IoT solutions, ensuring the food safety in FSCs [61,72], such as sharding, novel smart contract mechanisms, distributed and off-chain data storage solutions and platforms, such as IPFS and BigchainDB, to store large amounts of data from various origins, including sensor data. Various data access and data manipulation rights have been introduced with various encryption algorithms, such as ZKP [58], homomorphic encryption or attribute-based encryption, to improve the aspects of security, privacy and confidentiality in such applications. However, the privacy concerns, especially with the introduction of the general data protection regulation (GDPR), are still an on-going challenge in industrial and research applications [23,26]. The summary of solutions for the challenges of scalability, security, and privacy, presented in the analyzed literature, is depicted in Table 4.

There are existing challenges regarding process standardization, organizational/infrastructure regulation [4,19,20,28,68], interoperability [12,34,39,40,73] digitalization barriers [38,68,74], and sensory battery life [68]. Integration with GS1 standards, such as electronic product code information services (EPCIS), and digital food record were suggested to improve interoperability of blockchains in FSCs, to increase the levels of trust and to provide evidence of data provenance [36]. It has been suggested to consider various cross-regional and international food and feed legislation standards, such as EC 178/2002, when developing smart contracts [23].

**Table 4.** Summary of solutions to address the scalability, security, and privacy challenges.

Challenges	Solutions	References
Scalability	IPFS for storing data off-chain	food and agri-food [51,52,55], agriculture [24,72], rice [54], food trade [23]
	sharding	food [50], trade [41]
	BigchainDB	food [56]
	Proof-of-Supply-Chain-Share	e-commerce [46]
	Lightning network	food [57]
	Lightweight data structures, Delegate Proof-of-Stake, Distributed Time-based Consensus, DoubleChain, grouping nodes into clusters	agriculture [24]
Security	Two-level blockchain	agri-food [58]
	Data access restriction	food [50], agri-food [58]
	Proof-of-Supply-Chain-Share, blockchain vaporization	food [46]
	Proof-of-Authority	trade [41]
	Proof-of-Object	food [63]
	Product serialization, path-based fund transfer protocol	perishable food [65]
Privacy	Ellipse Curve Cryptography, Diffie-Hellman, RSA, secure protocols (Telehash, Whisper)	food trade [23], agriculture [24]
	Lightweight data structures, proxy encryption	agriculture [24]
	Interledger, consortium blockchain	food [66]
	Peer Blockchain Protocol	trade [41]
	Interledger blockchain	food [66]
	Access rights restriction, two-way coding scheme	grain [67]
	On-chain and off-chain data storage	food trade [23], food [55]
	Improved partial blind signature, proxy encryption	agriculture [24]
	Zero-knowledge proof encryption	agri-food [58]

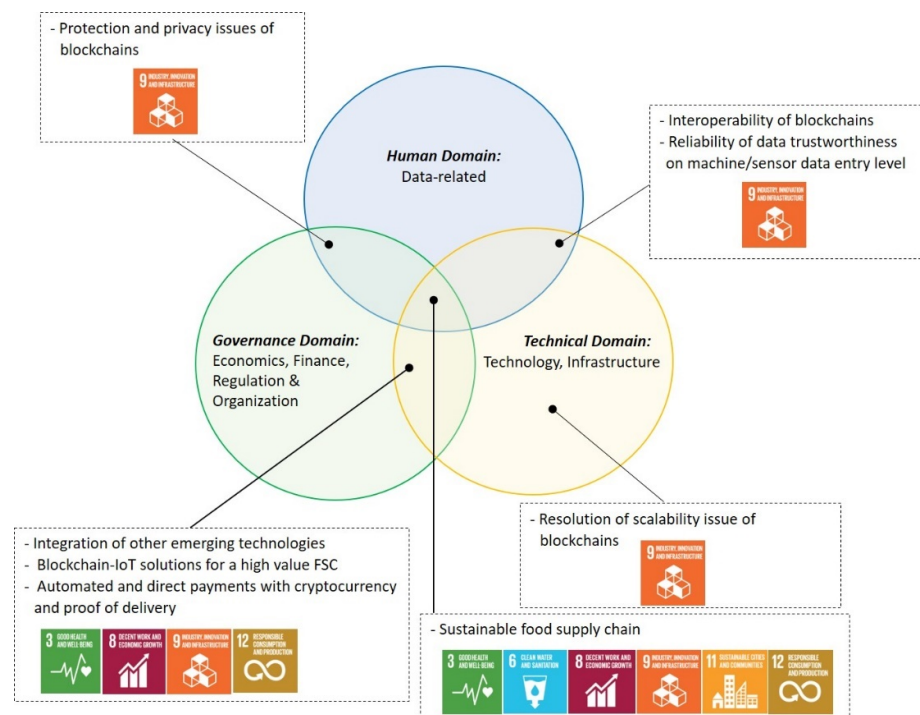
The issues of high costs and transaction fees of blockchain and IoT infrastructure implementation [12,19,41,48,49,70] were highlighted as some of the critical adoption challenges in FSCs, with several studies describing cost reducing impact [73,75], and effects on supply chain transactions with DLTs [75]. Additionally, various challenges and disputes might arise regarding infrastructure and data ownership [12,21], as well as data and sensor tampering [1,34,44,46,67], and information and data incredibility [73,76,77]. Due to the reluctance among FSC stakeholders [18] to implement DLT and IoT solutions, another major challenge is to involve stakeholders in DLT adoption in FSCs [25,59,78–80].

Despite the various challenges and barriers, there are numerous benefits of DLT and IoT implementation in FSCs. Several investigations were carried out to identify various enablers and value drivers of blockchain and DLT adoption in FSCs [81,82]. The key enablers identified were customer satisfaction, risk reduction, improvement of safety, improvement of quality of food [73,81], fraud detection, reduction of paperwork, provenance tracking, real-time transparency/visibility [7,73,81], improved systems, data security, and government regulations [81]. Depending on the sought value, the available

resources, feasibility of implementation [34] and various blockchain maturity levels and development stages (e.g., 1.0, 2.0, 3.0) should be considered when deciding on DLT adoption [19,43,82]. Several techno-economic factors, such as disintermediation, traceability, and price, were highlighted as the most important factors, which can influence stakeholders' adoption decisions [80]. However, there are issues, which blockchains alone cannot address, such as identifying which information should be shared with stakeholders versus private, confidential and competitive information, that should be protected and stored off-chain to achieve fair, trustworthy and sustainable FSCs [4,25]. Hence, tackling various data, technology, process standardization, and policy making issues is critical to facilitate blockchain and DLT adoption in FSCs [4,25,35].

#### 4. Implications for Future Research Directions

The aim of this review was to consolidate prior studies on blockchain, DLT, and IoT applications in FSCs using the SLR technique. Most of the studies were published recently, which demonstrates that the application of blockchain and DLT in FSCs is still in an early development stage. Moreover, despite the explicit benefits of blockchains and DLTs, there are various challenges associated with implementation and suggestions for future research directions to be addressed. Based on the presented findings, the future research directions are elaborated for the blockchain and DLT research and development in FSCs in a proposed domain scheme, adapted from [83], as shown in Figure 5.



**Figure 5.** Classification of the potential future research directions in blockchain-based FSCs, adapted from [83].

As it is presented in Figure 5, there are three domain schemes, which are human, governance and technical domain. The human domain includes data-related issues, while the governance domain includes the economics, finance, regulation, and organization related issues. The technical domain includes the technology and infrastructure associated issues. The potential future research directions for blockchain-based FSCs can be observed as highly interdisciplinary, as most of them overlap with at least with two other domains. These future research directions (FRDs) will be explained further in detail, with their contributions to the SDGs of the UN, considering the previous studies [17,18,84].

#### *4.1. Resolution of the Scalability Issue of Blockchains*

The scalability of blockchains is a known challenge and has been an active area of research for several years [60]. The scalability challenge is a major concern of blockchain-based systems for FSCs, because of growing data [51,58] and transaction speed [13,42]. The ongoing research should include the exploration and adoption of decentralized storage solutions, such as IPFS, BigchainDB, Swarm, IOTA, and Algorand, to store data off-chain [23,55,57]. In addition, to improve the scalability of the blockchain, the solutions involving fewer interaction with the blockchain should be considered, such as the routing protocols and routing algorithms for offline channels [65]. Further research and development of novel mechanisms are still needed to improve the scalability of blockchain-based applications in real business environments [47]. This FRD can be considered in response to the SDG 9, industry, innovation and infrastructure.

#### *4.2. Data Security, Reliability and Trustworthiness at Machine or Sensor Data Entry Level*

The data security and trustworthiness are some of major challenges of the blockchain and IoT-enabled applications [38]. Therefore, novel consensus algorithms should be further explored to facilitate the data access restriction on the blockchain [23,63]. IoT devices are widely integrated in various blockchain deployments, capturing food production data and environmental conditions during distribution processes, thereby decreasing labor costs and improving data entry credibility [44]. Since the data are stored permanently in blockchains and DLTs, such data can be utilized for subsequent processing (e.g., traceability, verification, recommendation, and payment), ensuring the accuracy of recorded data. An additional challenge has been the possibility of mismanagement and tampering of IoT data, which magnifies security and data reliability concerns [7,13,36]. Further research efforts should be targeted at developing fault-tolerant, safe and reliable architectures and systems for blockchain-IoT-based FSCs [1,63,67]. In addition, the application of fog computing concepts to improve the reliability of IoT devices could be investigated [85]. This FRD can be considered in response to the SDG 9.

#### *4.3. Protection and Privacy Issues of Blockchains*

One of the major challenges of blockchain-IoT applications is the compliance with existing regulations and standards [25,35,51], as well as harmonization of standards for cross-regional and cross-country FSCs [25]. Regulatory authorities are setting rules of data protection, such as the GDPR on the data protection and privacy in the European Union and the European Economic Area. The users of blockchain-based FSC solutions should be taught to consider and interpret their rights, obligations and duties. Smart contracts can potentially ensure compliance with legislations, as well as the protection of participants' privacy. Therefore, future research initiatives should concern the data protection mechanisms (e.g., homomorphic encryption, attribute-based encryption, etc.) and privacy issues of blockchains and DLTs [20,40,66]. This FRD can be considered in response to the SDG 9.

#### *4.4. Interoperability of Blockchains*

The blockchain interoperability refers to the ability to share information across different blockchain networks without restrictions. The blockchain interoperability can be categorized in the following forms: (1) the interoperability between blockchain and legacy systems; (2) the interoperability between blockchain platforms; and (3) the interoperability between two smart contracts within a single blockchain platform [86].

Even though there are currently several blockchain project initiatives in the FSC domain, most of these projects are isolated and unable to communicate with each other. The blockchain interoperability can be considered important, particularly, in the FSC domain, which generally consists of various relevant stakeholders [36,49,66]. Each stakeholder may have their own system, that is not compatible with the other stakeholder's system. Therefore, blockchain developments should be flexible enough to

consider various regulations and platforms [4,22]. The formation of consortia of business partners, supported by governmental institutions, was suggested to drive standardization of blockchain developments and the long-term implementations [4,7]. Consequently, topics concerning the development of general standards for data collection and exchange, as well as standardization of processes and interfaces to enhance interoperability across different systems and blockchain solutions, as well as the integrity of data still require further attention to enable efficient cross-medium and cross-blockchain communication [4,12,23,42]. This FRD can be considered in response to the SDG 9.

#### *4.5. Integration of other Emerging Technologies*

Blockchain technology is utilized as a solution for trust and security issues among FSC stakeholders [4,5,7]. Additionally, smart contracts can be utilized to detect nearly expired food products. Therefore, a warning or alert system could be introduced, so that retail stores could manage, distribute, or sell products before the expiration date. Furthermore, the blockchain becomes the underlying technology, that can be integrated with other emerging technologies (e.g., artificial intelligence (AI), big data analytics, digital twins, cloud- and fog computing) to realize data-driven FSCs [12,48]. The combination of the blockchain, IoT and machine learning is one of the promising topics to explore. On the one hand, the blockchain is utilized to store data in a permanent and immutable way to guarantee reliability; on the other hand, AI, such as machine learning or deep learning, can examine existing data and construct algorithms, that can make predictions to identify patterns, or to generate useful recommendations, thereby creating a medium for data-driven decisions [24,81,87]. Therefore, the integration of blockchains with other emerging technologies can contribute to development of innovative solutions in agri-food and precision agriculture domains to increase yields, while reducing production costs and environmental pollution [26]. This FRD can be considered in response to the SDG 12, responsible consumption and production, and SDG 9.

#### *4.6. Blockchain-IoT Solutions for a High Value FSC*

Only a few studies have focused on developing IoT-based blockchain solutions for organic or premium FSCs, which could sustain consumers' trust in authentic and organic product origin in FSCs. Hence, another important dimension for future research is the application of blockchains in combination with the IoT in FSCs to verify the authenticity of organic food products [7,19]. IoT-based sensors integrated in FSCs ensure the reliability and availability of data. The DLT, on the other hand, is a more reliable, credible, and secure counterpart to a traditional database. Therefore, organic certification processes can be facilitated and automated with integrated blockchain, DLT and IoT solutions [7,88]. Furthermore, a digital certificate with anti-counterfeit evidence, issued with blockchain, is much more trustworthy and can be easily verified, compared to a paper-based counterpart. Hence, further research on IoT-based blockchain solutions for organic FSCs and the subsequent evaluation of FSC performance is worth investigating. This FRD can be considered in response to the SDG 3, good health and wellbeing, and SDGs 9 and 12.

#### *4.7. Automated and Direct Payments with Cryptocurrency and Proof-of-Delivery*

Traditional trading methods are time-consuming and rely heavily on manual processes to handle transactions in FSCs. Furthermore, in addition to these complex and inefficient practices, payments are time consuming and are carried out through financial intermediaries [89,90]. For this issue, the blockchain technology can provide the medium for automated and direct payment processes. The future research initiatives should consider adopting blockchains for automated payment transaction processes with cryptocurrencies and proof-of-delivery methods integrated between senders and recipients [20]. Such an automated payment system with cryptocurrencies or currency-like transactions can help eliminate the need of trusted third parties or unnecessary human interventions, leading to



payment delays [12,21,90]. Additionally, initiatives to support small farmers can be introduced, increasing their competitiveness in developing markets, establishing cooperatives [19], and improving their profits [88,90]. Moreover, performance evaluations and cost analyses of such solutions in empirical and case study-based settings should be investigated. Prior studies highlighted the importance of blockchains in addressing the labor and decent work conditions, ethical issues, animal welfare and environmental impact issues, related to the SDG 8 [25,84]. Therefore, this FRD can be considered in response to the SDG 8, decent work and economic growth, and SDG 9.

#### 4.8. Sustainable Agri-Food Supply Chain

Blockchains or other DLTs in combination with IoT are considered as some of the most promising technologies, that can potentially enable connected and traceable supply chains, more decentralized, trusted, and user-centered digital services, as well as new business models, that could benefit the society and economy. They could additionally enhance the sustainability of various agri-food supply chains [12,19,33,91].

Previous comprehensive research on blockchain and DLT development was demonstrated with proof-of-concept and prototypical implementations in FSCs. However, there is still a lack of empirical validation to evaluate the impact of blockchains and DLTs on FSCs performance [22,37], in particular, related to sustainability, i.e., economic, social, and environmental sustainability. For instance, with regard to the economic aspect, future research initiatives should evaluate how blockchains and DLTs can help reduce economic losses and food waste, or how such solutions can enhance the circular economy aspects of FSCs [17,84]. The economic sustainability of blockchain-enabled solutions needs to be evaluated, reflecting on the adoption potential of the blockchain technology in real business environments. However, the barriers to engage all relevant stakeholders in FSCs to adopt the blockchain [13,84] should be considered, which can hinder the adoption process.

From the point of view of the social sustainability aspect, the future research initiatives should address the legal and regulatory issues of blockchain-based systems [13,25,58,73,84]. Various initiatives promote global blockchain standards, such as ISO Blockchain (TC307), to facilitate industrial and societal acceptance [13]. Besides, further studies to improve working conditions and to monitor forced labor in FSCs should be carried out, measuring the real social sustainability of FSCs through blockchain utilization.

The blockchain-based IoT applications can record permanent data of the entire activity in a FSC from the food production (e.g., cultivated plants, fertilizers, pesticides), transportation, processing, and packaging to the retailing of food products. However, complex consensus mechanisms to validate blockchain transactions require high energy consumption [42]. Therefore, the investigation of “lightweight” distributed consensus mechanisms is necessary to address the energy consumption challenge and to consider an environmental sustainability perspective in blockchain deployments [26]. Providing reliable and detailed product information on food origin, logistics details, production, and distribution details can empower consumers to make informed and responsible purchasing decisions [12,18,19,21], taking into consideration the sustainability of food industries involved, thereby enabling sustainable consumption in FSCs [12,19,21]. Ethical and sustainable food production [22], addressing fair income and poverty issues [17,18], responsible consumption and purchasing decisions [17], and global partnerships for sustainable development [17] can potentially support the achievement of the SDGs. Synergies and various trade-offs between targets can be investigated, addressing the issues of decent work, health, economy, social inclusion, sustainable water management [10], and reduction of industrial, municipal, and agricultural waste with blockchains [17,18]. Once the sustainable FSCs with those three dimensions of sustainability (i.e., economic, social, environmental) can be established, it can lead to the achievement of the

SDGs, particularly, the SDG 6, clean water and sanitation, SDG 11, sustainable cities and communities, and SDGs 3, 8, 9, and 12.

Various additional SDGs were addressed in literature, which can benefit from blockchains; however, mostly indirectly, such as the SDG 1, no poverty [17,18], SDG 4, quality education [17], SDG 5, gender equality [18], SDG 10, reduced inequalities [17], SDG 14, life below water [18], and SDG 17, partnerships for the goals [17]. The abovementioned suggestions for future research demonstrate, that there are still numerous topics in blockchain innovation and implementation to investigate, in order to establish digitally connected, traceable and sustainable FSCs, which can potentially contribute towards the SDGs achievement.

## 5. Discussion

Apart from the challenges of scalability, security, and privacy, the challenges of technical, organizational, and regulatory origin in blockchain-based FSCs [22] were highlighted, including the technological immaturity [23], and adoption barriers [4,84], providing implications for research directions [13,17,22,33,84]. The lack of national and international regulations and standards [35], high costs for blockchain development, gas consumption [53,58,92] and substantial energy and computing power consumption [57,92] can hinder the industry-wide adoption in FSCs [22]. Additionally, the interoperability of DLTs should be investigated, including blockchain-to-blockchain and blockchain-to-legacy interoperability [36]. Development of consortia of business partners, supported by governmental institutions, was suggested to drive blockchain standardization and long-term implementation [4]. Various barriers of data entry at the physical level still persist, such as data and sensor tampering, which can be tackled with full digitization, full visibility and substantial investments [7]. Therefore, cost and benefit factors, consumers' willingness to pay and product value or volume might play a role in blockchain adoption decisions [7].

Contribution of blockchain technology towards sustainability of FSCs [22] and the SDGs in the areas of health, economy, decent work, reduction of waste, sustainable water management, and social inclusion was highlighted [17,18,84]. More efforts should be dedicated to make blockchain, DLT, and IoT solutions in FSCs more sustainable, energy- and cost-efficient. Recent studies provide evidence, that internationalization of various economic activities on a world-wide level are necessary for development of coherent policies for the SDGs, as well as understanding of various synergies and trade-offs associated with market instruments to implement the SDGs [84,93]. The impact of disruptions, such as COVID-19, on global markets, economies and practices is additionally highlighted, since the disruptions bring in efforts for policies, strategies and planning on international level [93]. Therefore, novel supply chain processes should be designed to address the impact of disruptions on organizations, societies and FSCs [24].

Apart from the technological and policy initiatives, novel approaches and standardizations to automatically measure food quality and safety should be adopted, such as HACCP, DNA barcoding, DNA profiling [45], food quality index evaluation [94], and combination of different methodologies [45]. Implementing other emerging technologies, such as AI, digital twins, CPS, cloud- and fog computing and big data analytics, can ensure data-driven decision making in FSCs, as well as enhanced transparency, traceability and automation [22]. Digitalization initiatives, such as Agriculture 4.0 [42], can enhance the safety and reliability of food chains, as well as reduce food waste and food fraud. Empowering consumers with reliable and sufficient food data can enable responsible consumption and purchasing decisions in FSCs [12,19,84]. More empirical and case study investigations are necessary to evaluate technological capabilities of blockchains, the long-term benefits and quantitative aspects affecting FSC performance and sustainability [5,7,22]. The suggestions for future research directions and the summary of challenges, elaborated in this review, can benefit the ongoing DLT and IoT initiatives in FSCs.

## 6. Conclusions

This review provides a contribution towards outlining the current practical applications of blockchain, DLTs and IoT in the FSC domain, describing the initiatives to address the most relevant challenges of scalability, security, and privacy and suggestions for future research directions. The detailed analysis of the 69 shortlisted papers was provided with a comprehensive summary of existing solutions, challenges, and applications. Six strategic SDGs of the UN can potentially be addressed by the DLT and IoT implementation in FSCs, thereby enabling more traceable, transparent and sustainable FSCs. There are several limitations in our study. Papers published after December 2020 were not considered in the review, and due to the specifics of the search, there are publications that may have been missed. Further research should focus on considering other related supply chains, such as textile, e-commerce, food trade, agriculture, perishable and frozen food, processed food, global and local retail industries, packaging, and grocery networks, as well as investigating the impacts of other emerging technologies, mentioned in this study, on sustainability, transparency and traceability of FSCs. Furthermore, other highlighted challenges, presented in this study, such as regulatory, standardization and interoperability issues, should be addressed in more detail.

**Author Contributions:** conceptualization, J.N., U.P., T.M., and G.R.; methodology, J.N., U.P., T.M., and G.R.; validation, J.N. and U.P.; investigation, J.N. and U.P.; data curation, J.N. and U.P.; writing—original draft preparation, J.N. and U.P.; writing—review and editing, J.N., U.P., T.M., and G.R.; visualization, J.N. and U.P.; supervision, T.M. and G.R.; funding acquisition, J.N., U.P., and T.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This paper was jointly supported by OeAD-GmbH/ICM in cooperation with ASEA-UNINET and funded by the Austrian Federal Ministry of Science and Research (BMBWF), project number ICM-2019-13796; the Lower Austrian Research and Education Promotion Agency (NFB) dissertation grant number SC18-015; and Austrian Blockchain Center, project number 868625, financed by The Austrian Research Promotion Agency (FFG).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

FSC	Food supply chain
ISO	International Organization for Standardization
IoT	Internet of Things
DLT	Distributed ledger technology
CPS	Cyber-physical systems
GPS	Global positioning system
GIS	Geographic information system
NFC	Near-field communication
RFID	Radio frequency identification
SDGs	Sustainable Development Goals
UN	United Nations
AI	Artificial intelligence
SLR	Systematic literature review
CPU	Central processing unit
HACCP	Hazard control and critical control point
IPFS	Interplanetary file system
DOS	Denial-of-service
DDOS	Distributed denial-of-service

RSA	Rivest-Shamir-Adleman
CO2	Carbon dioxide
SSL	Secure sockets layer
TLS	Transport layer security
ZKP	Zero knowledge proofs
GDPR	General data protection regulation
EPCIS	Electronic product code information services
FRD	Future Research Direction
COVID-19	Coronavirus disease 2019
DNA	Deoxyribonucleic Acid

## Appendix A

**Table A1.** Classification of selected literature by application domain, publication type, year and research method.

Application	Publication	Year	Research Method	Reference
seafood	conference	2019	Case study	[74]
	journal	2019	Review	[45]
agriculture	journal	2020	Review	[24,43]
agri-food	journal	2019	Review	[19,21]
		2020	Review, case study	[73]
		2020	Case study	[79]
		2020	Review	[12,38]
		2018	Review	[1]
		2020	Experimental setup, simulation	[52]
		2020	System design, case study	[58]
olive oil	conference	2019	Experimental setup, simulation	[69]
dairy	book chapter	2019	Experimental setup	[95]
	journal	2020	System (framework) design	[59]
	book chapter	2020	Review	[6]
egg	journal	2019	Case study	[68]
agri-food	conference	2018	Experimental setup	[49]
		2020	System design, simulation	[53]
		2016	System (framework) design	[76]
		2019	System (framework) design	[71]
		2017	Case study	[56]
		2019	System (framework) design	[47]
		2019	Case study	[51,66]
food	conference	2020	Experimental setup	[61]
		2019	Case study (containerized)	[70]
		2020	Review	[39]
		2019	Experimental setup, simulation (milk chocolate)	[50]
		2019	System (framework) design	[44]
halal food	conference	2019	Experimental setup	[48]
	journal	2020	Case study	[78]
pork meat, restaurant	journal	2019	Experimental setup	[94]
grain	journal	2020	System design, simulation (Australian)	[92]
		2020	Case study	[67]
precision agriculture	journal	2020	System design (framework)	[85]
		2020	Review	[26,42]
Trade/food trade	journal	2019	Review	[41]

		2020	System (framework) design	[23]
rice	conference	2020	System design (framework)	[54]
		2020	Review	[77]
agriculture	conference	2020	System (framework) design	[72]
		2020	System (framework) design	[90]
		2020	System (framework) design	[88]
		2018	System (framework) design	[60]
		2019	Experimental setup	[63]
		2020	Experimental setup	[57]
		2020	Review	[25,31,33–35]
food	journal	2020	Simulation (quantitative study)	[81]
		2019	Review	[40]
		2019	Case study	[46]
		2019	Case study (case 2)	[75]
		2020	System (framework) design	[55]
soybean	conference	2019	System (framework) design	[20]
wine	journal	2019	Case study	[91]
food	book chapter	2020	Review	[36,37]
perishable food	journal	2020	System design (method)	[65]
seed	conference	2020	System (framework) design	[64]
retail	journal	2020	Experimental setup	[96]
grape	journal	2020	System (framework) design	[80]
fish	journal	2020	Case study	[18]
livestock	conference	2020	System (framework) design	[62]

## Appendix B

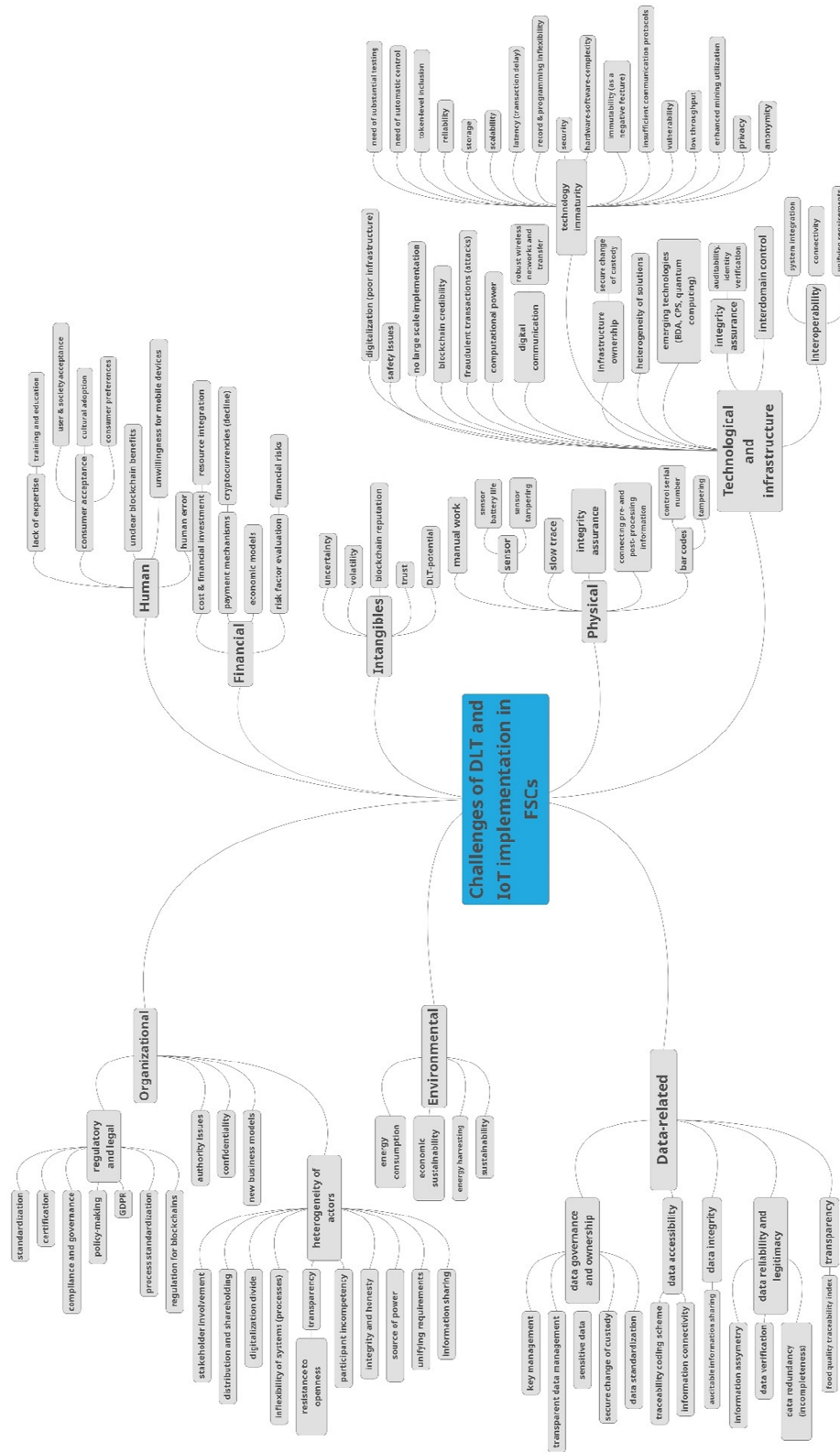


Figure A1. Challenges of DLT and IoT implementation: visualization of 8 thematic clusters and their keywords.

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