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Review

Digitalization and Future Agro-Food Supply Chain Management: A Literature-Based Implications

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Abstract: Achieving transition towards sustainable and resilient food systems is a critical issue on the current societal agenda. This study examined the potential contribution of digitalization of the food system to such transition by reviewing 76 relevant journal articles, indexed on the Scopus database, using the integrative literature review approach and descriptive content analysis with MAXQDA 2020 software. 'Blockchain' was the top hit among keywords and main concepts applied to the food system. The UK as a country and Europe as a continent were found to lead the scientific research on food system digitalization. Use of digital technologies such as blockchain, the Internet of Things, big-data analytics, artificial intelligence, and related information and communications technologies were identified as enablers. Traceability, sustainability, resilience to crises such as the COVID-19 pandemic, and reducing food waste were among the key benefit areas associated with digitalization for different food commodities. Challenges to practical applications related to infrastructure and cost, knowledge and skill, law and regulations, the nature of the technologies, and the nature of the food system were identified. Developing policies and regulations, supporting infrastructure development, and educating and training people could facilitate fuller digitalization of the food system.

Keywords: agro-food supply chain management; blockchain; digitalization; IoT; sustainability; sustainable food system; traceability

Citation: Amentae, T.K.; Gebresenbet, G. Digitalization and Future Agro-Food Supply Chain Management: A Literature-Based Implications. *Sustainability* **2021**, *13*, 12181. https://doi.org/10.3390/su132112181

Academic Editors: Alessio Ishizaka and Andrea Appolloni

Received: 5 August 2021
Accepted: 26 October 2021
Published: 4 November 2021

1. Introduction

1.1. Subject Highlight: Supply Chain Management and Agri-Food Supply Chain Management

According to [1] (p. 3) supply chain management (SCM) is defined as "*the management of upstream and downstream relationships with suppliers and customers in order to deliver superior customer value at less cost to the supply chain as a whole*". According to the author, supply chain management is a process through which relationships between parties in the chain are managed to incorporate individual interests into common interests for benefit of the chain as a whole. It is unarguable that supply chain management has an indispensable role in the current world. For instance, Ref [2] indicated the critical role of SCM to coordinate and efficiently control the material, information, and finance flows for the global market and trade to function properly. The author noted the important role of supply chain management in establishing a network of firms, suppliers, transportation systems, logistics hubs, and production units. Similarly, Ref [3] asserted that supply chain management is the foundation for the execution of operations and as the core of 21st-century business functions. Nowadays, the business environments are requiring supply chain management theories and principles to be synergized by the recent developments of digital technologies. Some scholars are referring the supply chain management in the era of the fourth industrial revolution (Industry 4.0) as "*SCM 4.0*" [4–6].

The success of supply chain management lies in the capabilities of the group-based and the whole chain-centered supply chain managers' capabilities in making quality decisions within the complex real-world constraints. The test of capabilities of the supply chain managers in handling conflicting interests, minimizing total costs along the chain, fulfilling customers' ever-changing demands, and achieving the social, economic, and environmental sustainability requirements lies on the quality of the decisions they make both at strategic and operational levels. In this regard, the understanding and use of decision-making tools by supply chain managers are critically important. Due to such importance, the decision-making tools and models for SCM are attracting researchers and practitioners resulting in developed innovative decision-making tools and models, which were found reliable with different real-world scenarios. Interested readers on such decision-making tools and models for SCM, may refer to the "*enterprise-wide optimization*" by [7]; "*short and long-run models for optimization of the supply chains of imports of containerized goods*" by [8]; "*optimization approach for supply chain management models with quantity discount policy*" by [9]; "*hybrid simulation-based optimization framework to solve the supply chain management problems*" by [10]; "*comprehensive solution for designing distribution networks in food supply chains that optimizes the network in three dimensions of costs, responsiveness and environmental conservation*" by [11]. These are only a few examples of the vast literature dealing with optimization decision models along the supply chain. Further, it is worth noting the works of [2,12–17] for multi-criteria decision-making (MCDM) models to handle various constraints in supply chain management.

The applications of digital technologies such as machine learning, blockchain, Internet of Things (IoT), and artificial intelligence (AI) in supply chain management are the recent phenomena that attracted researchers, innovators, and practitioners for their enabling features in handling huge information, finding out patterns of complex relationships and enabling to make proper and reliable decisions along the supply chains [17–23]. All decision tools and models for the supply chain management are aimed at the best use of technology and resources to improve efficiency and performances to enable customers' needs and wants satisfied and the organizations in the chain to become profitable, and their activities remain sustainable.

Even though there are tendencies of promoting local foods and short food supply chains with traceability and sustainability concerns, most of our food commodities are produced thousands of miles away from their consumption points. Agri-food supply chains (AFSCs) link the point of production and the point of consumption of the food products. Agri-food supply chain management (AFSCM) refers to "*the management of the relationship(s) among the raw material supply for agricultural production, production, processing, and product logistics and distribution*" [24] (p. 1). The authors noted the lack of specific literature in the supply chain management (SCM) defining agri-food supply chain and/or agri-food supply chain management, which could arise out of considering AFSCM as a branch of SCM. Hence, similar to SCM, the AFSCM may be defined as the process of managing upstream and downstream relationships in food supply chains in order to deliver high-quality and safe foods to consumers at a fair price. However, ref [25] asserted that due to the factors such as food-related diseases, seasonality, shelf lives, the need for accurate information on the ingredients and the expiry dates, perishability, sustainability, safety, and other peculiar constraints to the food sector, AFSCM seeks more innovative and advanced models and approaches to handle complex issues along the food chains. Concerning the decision models used with food supply chain management, interested readers may refer to [25]. The authors after review of the literature identified and assessed the commonly used models such as mixed-integer programming, linear programming (LP), meta-heuristics, multi-objective programming, stochastic programming, and fuzzy logic simulation or analytical models and proposed a new model termed as "*a constraint-driven approach to food supply chain management*." The authors asserted the new model would be data-driven, allow flexible modeling and solving FSCM problems, and would lead to a better and more realistic representation of the problems to be modeled. Equivalent to decision models, agro-food supply chain managers should also be aware of the growing tendencies for authoritative evaluations and certifications of the whole food supply chain activities, particularly for environmental concerns. One of such environmental policy instruments is the Green Public

Procurement (GPP), which is an instrument used to evaluate the food sectors' carbon footprint [26]. The European Commission (2008) as cited in [27] (p. 75) defined Green Public Procurement (GPP) as "*a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured*". GPP as a concept relies on the use of public authorities' purchasing power to shape consumption and production trends, thereby increasing demand, and altering the market structure in favor of more environmentally friendly products [28]. Though the detail of GPP is not within the scope of the current review, it is important to mention the important role of digitalization for GPP. For instance [29] discussed supply chain management sustainability and supplier selection within the framework of digitalization, "*digitalized and green supplier selection (DG-SS)*". For further insights about GPP, interested readers may refer to [30–33] among other available literature.

Overall, as with SCM, the use of digital technologies in agri-food supply chain management is evolving. This paper attempted to present an overview of the existing digitalization of the whole agri-food system, available digital technologies, their applications, and challenges arising thereof, for policy decision-makers, researchers, and inventors dealing with the food system for appropriate preparedness to enable the sustainable food system transitions.

1.2. Background of the Study

The world is well into its Fourth Industrial Revolution (Industry 4.0), where many things in the human environment from work life to daily life, including food, exercise, and personal habits, are affected by emerging technologies. Moreover, all sectors of the economy, including industry, agriculture, trade, mining, defense, and politics, face emerging opportunities and threats caused by the rise of robotic technologies. This demands more focus on intellectual capital in the discipline of digitalization along the spectrum of human life and economic sectors.

Food system research has long been an important item on the global agenda. A current critical task for stakeholders in food sector disciplines is to identify ways to transition towards economically, socially, and environmentally sustainable and resilient food systems. For instance, the United Nations (UN) Food Systems 2021 Summit (The Tokyo Nutrition for Growth (N4G)) reflected on the importance of shifting policies and strategies used to feed the world during the Twentieth Century [34]. Among major issues identified at the Summit, it was concluded that without decisive actions for transitions of the food system, the goals for universally accessible, affordable, and healthy diets delivered by the food systems which are environmentally, economically, and socially sustainable are unthinkable [34]. Research issues that may arise when addressing the target of food system transition include (i) how to move towards more healthy, sustainable, and inclusive food systems, which may require starting from production, distribution, consumption, and disposal in a very different manner; (ii) whether digitalization of the food system or use of digital technologies can help achieve these objectives; and (iii) future directions for researchers and policymakers. Based on a review of the recent literature, this paper describes possible solutions through digitalization of the food system.

1.3. Research Gap and Significance of This Review

Digitalization has already attracted research interest in terms of achieving the United Nations Sustainable Development Goals (SDGs) and as a means for sustainability [35–37]. Consequently, the benefits, opportunities, and challenges of food system digitalization are currently the topic of much scientific discussion [38–43].

Table 1 presents some recent literature reviews on food system digitalization. As can be seen from Table 1, the literature described application areas for the specific digital technology studied. However, it is worth noting that though the literature described clear benefits associated with the application of the studied digital technologies to the food system, including improving competitiveness in agro-food supply chains and food safety, and achieving sustainability targets, the literature were specific to a single or few related technologies. To our knowledge, no previous publication has comprehensively reviewed digitalization of the whole food system with the full spectrum of digital technological applications. Moreover, little attention has been paid to specific food commodities, food supply chain problems, and where in the world digitalization of agro-food chains is being researched and applied. Another overlooked issue is the comprehensive assessment of challenges associated with food system digitalization. Similar to the benefits, the literature discussed challenges specific to a certain technology or a few related. Therefore, this paper represents the first attempt at a comprehensive review of digitalization of the whole food system, including all digital technological applications available, challenges arising in digital technology application to the food system for policymakers, researchers, inventors, and stakeholders, and the importance of awareness and preparedness. The aim of the review was to fill these research gaps and provide new comprehensive insights on digitalization of agro-food supply chains, thereby complementing the existing literature.

Table 1. Some recent review papers on food system (FS) digitalization. (Source: created by authors).

Author(s)	Digital Technology/ Concept Studied	All Available Digital Technologies Applicable to the FS Identified	Application Areas for the Studied Digital Technology Identified	Food Commodities with High Uptake of Digitalization Identified	Global Distribution of FS Digitalization Identified	Challenges of Application of the Technology Identified
[24,44]	IoT, blockchain,	X	✔	X	X	✔
[18]	Machine Learning	X	✔	X	X	✔
[45]	Fuzzy applications, big data, and GIS	X	✔	X	X	X
[46]	Big Data	X	✔	X	X	✔
[47]	Blockchain	X	✔	X	X	✔
[48]	Blockchain	X	✔	X	X	✔
[49]	Blockchain and IoT	X	✔	X	X	✔
[50]	IoT	X	✔	X	X	✔
[51]	ICT	X	✔	X	X	✔
[52]	Blockchain	X	✔	X	X	✔
[53]	Blockchain	X	✔	X	X	✔
[54]	Blockchain	X	✔	X	X	✔
[55]	Blockchain and IoT	X	✔	X	X	✔
[56]	Distributed Ledger Technology (DLT)	X	✔	X	X	✔
[57]	Big data analytic	X	✔	X	X	X
[58]	IoT	X	✔	X	X	X
[59]	Blockchain	X	✔	X	X	✔
[60]	IoT	X	✔	X	X	✔
[61]	IoT	X	✔	X	X	✔

Legend: ✔—Yes, X—No.

1.4. Objectives of the Review

The overall aim of the work was to review the recent literature (published 2017–2021) in the area of digitalization of the food system, in order to identify existing possibilities and challenges created by digital technologies in the transition towards a sustainable food system. Specific objectives of the review were to identify:

(1) The dominant digitalization technologies/concepts applied in food systems.
(2) Major problems in the agro-food supply chain addressed by digitalization.
(3) Food commodities with high uptake of digitalization.
(4) Global distribution of digital applications in the food system and of related scientific work.
(5) Challenges in digitalization of the food system.
(6) Implications for agro-food supply chain management and transition towards sustainable food systems.

2. Review Methodology

2.1. Review Approach

The literature review as a research method is important in generating theoretical frameworks and conceptual models by synthesizing multidisciplinary research findings [62]. There are three main approaches to literature reviews, systematic, semi-systematic, and integrative [62]. The integrative approach was selected for the present study because it best matched the purpose of the work, which was not to cover all materials ever published and archived in all databases on digitization, digitalization, and agro-food supply chain management, but rather to synthesize recent findings and assess the practical readiness for the transition towards a sustainable food system. Although all databases have their own pros and cons, Scopus was selected as the source of publications, based on its wider coverage of high-quality scholarly information and its user-friendly search options with institution/subscription accounts.

2.2. Literature Collection

The searches were made on the Scopus database using three alternative keyword combinations:

(a) (agriculture* AND food AND supply AND chain AND management) AND PUBYEAR > 2016) AND (Digital*),
(b) (food AND supply AND chain AND management) AND PUBYEAR > 2016 AND (Digital*),
(c) (Agro-food AND supply AND chain AND management AND PUBYEAR > 2016 AND (Digital*),

These keyword combinations yielded a total of 448 hits. After a rigorous review of the contents of abstracts, conclusions, and methodology of these 448 papers, 76 relevant journal articles were selected for the review. Inclusion/exclusion criteria applied were: the paper must discuss issues in agri/agro-food supply chains; and it must discuss issues related to digitization, digitalization, and/or use of digital technologies along food supply chains.

2.3. Scope of the Review

The scope was limited to English language journal articles published between 2017 and 2021, indexed in Scopus, and available through open access or through institution subscription by the Library of the Swedish University of Agricultural Sciences (SLU). Only journal articles were considered for the review, i.e., books, conference proceedings, and other reports were not included. Moreover, technical and methodological details in the selected articles were not the subject of the review.

2.4. Analytical Framework

After scrutinizing the selected journal articles, the data required to fulfill the specific objectives of the review were organized. From each journal article, the keywords, the digitalization concept applied, the main problem of the food system addressed/alleviated, the specific food commodity studied, the country/region concerned, the country/region of authors based on their affiliations, the research outcomes listed in concluding remarks, and the main challenges identified were extracted. These were subjected to data coding and analysis, using MAXQDA 2020 software. Visual tools within the MAXQDA 2020 software and Microsoft Excel 2016 were employed to plot the results of descriptive content analysis of the data.

2.5. Flow Chart for the Review Methodology

Figure 1 presents the flowchart for the overall methodology followed in this paper. As in any other paper, the paper was started through idea conceptualization and agreement on the main area of scrutinizing and preliminary title. Then, the interactive steps were passed to finally come up with the paper. The flowchart (Figure 1) is just the simplified sketches of the steps followed in the review process.

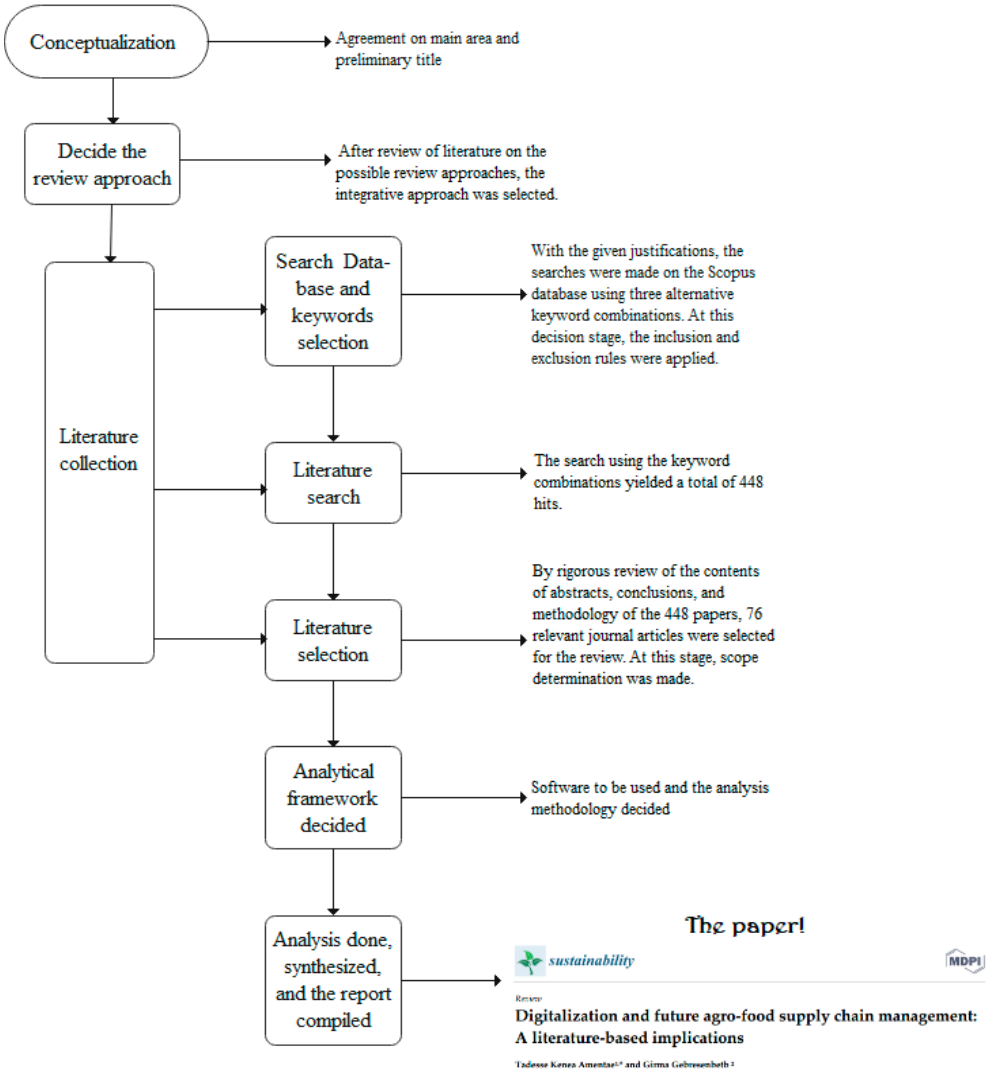

Figure 1. Flow chart of the review process (Source: drawn by authors).

3. Results and Discussion

3.1. The Dominant Digitalization Technologies Applied in Food Systems

In order to identify the dominant digitalization technologies/concepts applied in food systems, the keywords and main digitization/digitalization technologies/concepts examined in the selected journal articles were analyzed. In keyword analysis, words related to the specific method used, specific food commodity, and country of the study were excluded as not relevant to the research question or falling within other research objectives (see Sections 3.3 and 3.4). In order to clarify the meaning, keywords stated in phrases were hyphenated. For example, Internet of Things (IoT), a keyword phrase used by many journal articles and comprising three words in content analysis, became Internet-of-Things (IoT). The word cloud of keywords from all papers generated using MAXQDA 2020 software is depicted in Figure 2, and the main digital technologies/concepts addressed by the papers using frequency analysis are presented in Figure 3.

Figure 2. Word cloud of keywords from reviewed papers, with font size indicating frequency of mention. (Source: created by authors).

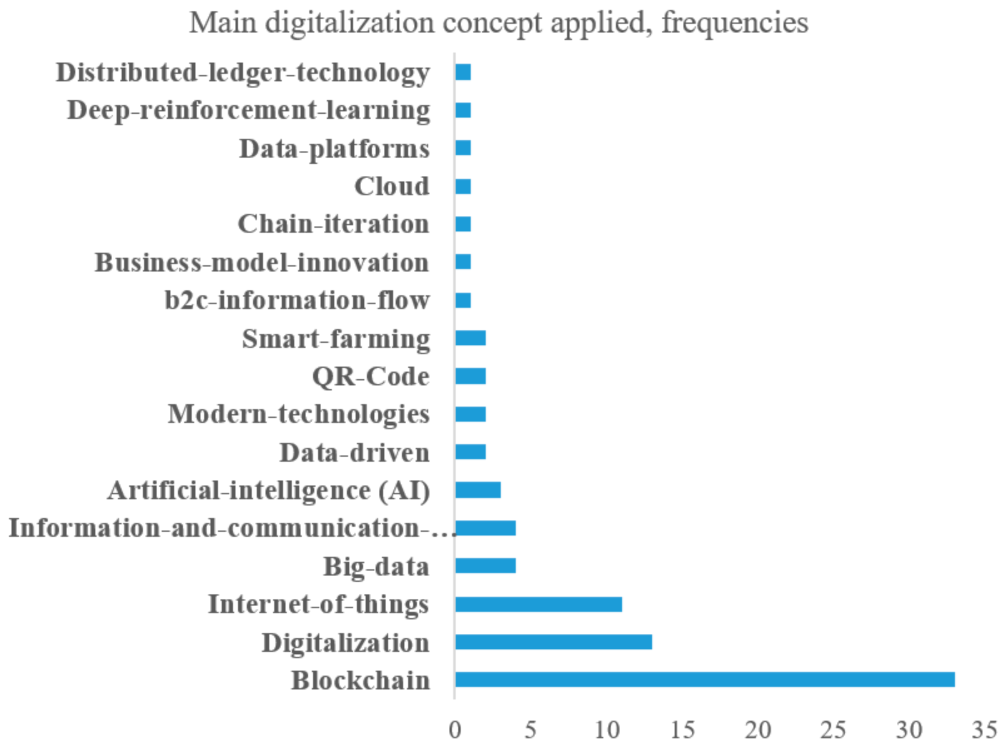

Figure 3. Digitalization technologies/concepts applied, frequencies of mention in the reviewed papers. (Source: created by authors).

As can be seen in Figure 2, blockchain was the top hit among keywords used by the papers reviewed. Blockchain was also the main concept applied to the food system in the papers (Figure 3). In keyword analysis, blockchain, traceability, Internet-of-Things/IoT, supply-chain-management, sustainability, food-supply-chain, big-data, food-loss-and-waste, food-supply-chain-management, digitalization, food-safety, agri-food-chain, digital-agriculture, food-security, precision-agriculture were identified as the top hit keywords used in the papers. Blockchain, digitalization, Internet-of-Things, big-data, information-and-communication-technologies (ICT), artificial intelligence (AI), data-driven, modern technologies, QR code, and smart farming were among top scientific discussion points in the reviewed literature (Figure 3). Note that the concepts addressed by many of the papers were similar and sometimes identical, owing to the inclusive nature of some terms. For instance, the term 'digitalization' includes other concepts. In this review, the terms were used as done in the reviewed papers. While presenting some of the specific concepts separately would have given better insights on specific issues within the main concept of digitalization, many papers opted to use the inclusive term digitalization when discussing two or more concepts. As an example, in papers discussing the integration of blockchain and IoT, the term digitalization was used in the analysis. Thus, digitalization was the second top hit concept used by the reviewed papers (Figure 3). However, it is important to note the meaning overlap in subsequent categorization of the main digitalization concepts applied to the food system in this paper.

In the results in Figure 2, the analysis of keywords, and the results in Figure 3, the main digital concepts applied to the food chain were quite related. This is of course because the main concept applied in the papers was mentioned in the keywords. Slight differences arose in the results because most papers used at least five keywords (sometimes phrases) but the main concepts of the papers were summarized into one or two concepts.

3.2. Major Problems in the Agro-Food Supply Chain Addressed by Digitalization (Main Application Areas)

From all papers reviewed, the main problems addressed by digital technologies or concepts were extracted. The data were then categorized and coded using the MAXQDA2020 software. They were categorized into five major areas, namely: traceability, sustainability, other performance issues along the food chain, other food supply chain management (FSCM) issues, and reducing food waste/loss. The categorization process, which was based on our understanding of the literature reviewed, is described in detail in Appendix A to this paper. Categorizing the main concepts addressed by the reviewed literature was not easy, as some concepts were related and some were inclusive of others. Categorization was performed as follows: all technologies or concepts aimed at traceability were categorized under traceability, including traceability itself, accountability, transparency, auditability, and others. All technologies or concepts aimed at sustainability, directly by mentioning the term or indirectly, were categorized as sustainability, including concepts such as sustainability, sustainable-performance, produce-more-food-more-sustainably, achieve-UN-Sustainable-Development-Goals, agro-food-sustainability-transitions, sustainable-food-systems, sustainable-food-supply-chain, sustainable-food-supply-chain-management, and related others. Technologies or concepts aimed at addressing broad performance issues along the food chain, such as productivity, quality, supply-chain-performance, precision-agriculture, smart-short-food-supply-chain, post-COVID-19 crisis response performance, and others, were categorized as other performance issues. Technologies or concepts related to food supply-chain-management (FSCM) not categorized into the other categories used here, such as supply-chain-management, distribution-management, risk-management, uncertainty-management, decision-making, agri-food-supply-chain-management, network-management, coordination, and others, were categorized under other FSCM issues. Finally, technologies or concepts attempting to deal with food loss and/or waste were categorized as reducing food waste.

After categorization, coding was applied. A summary of the main technologies or concepts addressed by the reviewed papers is presented in Figure 4. Based on the coding results, traceability was the top concept addressed by digitalization technologies/concepts along food chains in the papers reviewed. In second place was sustainability, with a significant number of papers discussing digitalization of the food system as a means to achieve sustainability in its different aspects (social, economic, environmental). Other papers discussed digitalization of the food system to resolve other performance issues along the food chain, other FSCM issues, and reducing food waste, in that order of frequency of mention (Figure 4).

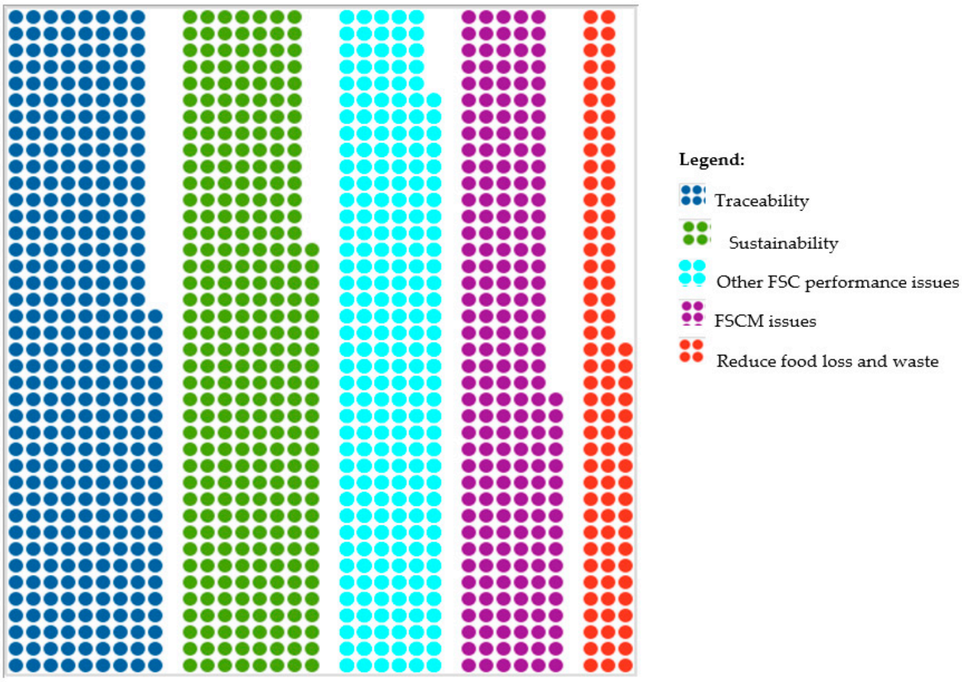

Figure 4. Main problem areas addressed by the reviewed papers, divided into five categories (left-to-right: traceability, sustainability, other performance issues in the food supply chain (FSC), other food supply chain management (FSCM) issues, and reducing food waste). (Source: created by authors).

Tables 2–4 list the concluding remarks from the papers organized in terms of the problems addressed within the categories considered here traceability (Table 2), sustainability (Table 3), and other performances, FSCM issues, and reducing food loss and waste (Table 4). As it can be seen from Table 2, significant proportions of the reviewed articles discussed the important role of digitalization of food systems in enabling food traceability. Smart contracts, transparency, auditability, recall efficiency, trusted tracking, real-time communications, and control of counterfeiting are some of the basic achievements along the food chains through food system digitalization as can be seen from Table 2.

Table 2. Main concluding remarks in the reviewed papers related to Trace-ability function. (Source-created by authors).

Source	Research Outcome from Concluding Remarks in a Single Statement (Focus of the Digitalization Concept and Main Problem/s Addressed)
[63]	Smart contracts using end-to-end blockchain-based agri-food supply chain solutions are efficient and robust in terms of traceability, trading, delivery, and reputation.
[17]	A blockchain-based framework combined with deep reinforcement learning (DRL) in food supply chain management (FSCM) provides reliable product traceability, higher profitability, and supply chain flexibility.
[64]	For small and medium enterprises (SMEs) in the Malaysian halal agro-food chain, technological advances such as IoT have high potential for achieving product traceability.
[65]	Traceability, price, trust, compliance, coordination, and control (in that order of relative importance) influence adoption of blockchain technology.

Table 2. *Cont.*

Source	Research Outcome from Concluding Remarks in a Single Statement (Focus of the Digitalization Concept and Main Problem/s Addressed)
[66]	A model for agro-food traceability can be developed based on comprehensive and quantifiable granularity concepts.
[67]	Continuous traceability between storage and logistics improves the breadth, depth, and precision.
[23]	A blockchain-based system guarantees food quality and process safety traceability.
[68]	Blockchain & IoT empower a transparent, auditable, and traceable food system.
[69]	Blockchain technology as the start of revolutionary food supply chain tools will allow consumers to really know where their food comes from (traceability).
[53]	Blockchain can help improve food traceability, information transparency, and recall efficiency.
[70]	Blockchain enhance FSCM and traceability in food distribution.
[71]	Asymmetries between traceability systems along the supply chain affect inventory and food quality.
[54]	Blockchain implementation improves traceability in the food system.
[72]	Use of blockchain technology in agri-food supply chains provides trusted track, trace, and provenance information to the focal firm and consumers that leverages efforts for sustainability.
[73]	Blockchain technology can be considered a true innovation and relevant approach to assure traceability and authenticity in the food supply chain, data acquisition and management.
[74]	AgriBlockIoT (integrated IoT and blockchain technologies) enables creation of transparent, fault-tolerant, immutable, and auditable agri-food traceability systems.
[75]	Digitalization considering blockchain effects is essential for sustainable agro-supply chain management (ASCM), due to the ease in product traceability, security, and transactions.
[76]	Blockchain supports non-tampering data, thus increasing consumer confidence in FSCM and food products; integration of blockchain with big-data analytics alleviates the slight data speed downside.
[59]	Blockchain overcomes privacy and security challenges through smart contracts, monitoring counterfeiting, and traceability systems to ensure food safety and security.
[77]	In food supply chains, increased transparency, traceability, and trust are direct attributes of blockchain-based technologies, while sustainability improvements are an indirect attribute.
[61]	Regardless of the challenges faced, introduction of new technologies such as IoT to the food chain has potential to make food production a truly transparent process.
[78]	A framework for reliable, auditable, and trackable FSCM ensures transaction integrity, immutability, and transparency of perishable products.
[79]	The decentralized E-supply chain model performs well in fresh produce supply chains from the perspective of quality protection through traceable information.
[80]	Implementation of big-data analytics, cloud computing, and IoT can transform and upgrade FSCM to a smart future and more sustainable and adaptive food supply chains.
[44]	Data-driven agri-food supply chains (AFSCs) are a means for sustainability of the food system.

Table 3. Main concluding remarks in the reviewed papers related to Sustainability function. (Source: created by authors).

Source	Research Outcome from Concluding Remarks in a Single Statement (Focus of the Digitalization Concept and Main Problem/s Addressed)
[18]	Machine learning (ML) techniques can benefit agriculture supply chains and lead to sustainability.
[45]	Geographic information system (GIS)-based fuzzy applications can be used in land suitability assessment, real-time crop quality inspections; real-time weather forecasting, locations models for cold storage, and real-time perishable agri-transportation model considering socio-economic factors, among others.
[46]	Food security, safety, and sustainability can be addressed through big data applications.
[47]	Blockchain technology can contribute to a more sustainable food industry and help to achieve traceability by irreversibly and immutably storing data.
[81]	To produce more food more sustainably, the use of digital technologies offers potential solutions.

Table 3. *Cont.*

Source	Research Outcome from Concluding Remarks in a Single Statement (Focus of the Digitalization Concept and Main Problem/s Addressed)
[82]	Smart technologies as tools can lead to customization of sustainable food supply chains.
[83]	Blockchain enables sustainability performance of supply chains and promotes United Nation Sustainable Development Goals (SDGs).
[51]	Information & communication technology (ICT) can contribute to agro-food sustainability transition.
[84]	A data-driven analysis framework that considers multiple aspects of food supply chains can help move sustainable planning beyond the traceability objective.
[85]	Frameworks of Industry 4.0 and models, algorithms, heuristics, and metaheuristics technologies can enable sustainability in food supply chains.
[86]	Artificial intelligence (AI) and digital technologies can help create sustainable business models that increase productivity, reduce production costs and emissions, and improve correspondence in markets.
[55]	Blockchain plays a vital role in food system sustainability.
[87]	Cloud computing provides useful metadata for digital certifications using global positioning system (GPS) and other sensor technologies, and satisfies the objectives of the sustainable business model by reducing transaction costs and strengthening alliances between stakeholders.
[88]	GIS-based analysis integrated with current data streaming and blockchain platforms enhances trust and sustainable integration of food supply chains.
[89]	A framework driven by AI technologies can contribute to sustainable financing stream for food and drink supply chains.
[90]	Blockchain technology has the potential to improve supply chain sustainability in the areas of environmental protection, social equity, and governance efficiency indicators.
[41]	In some regions, the current adoption of digital agriculture appears to be driven more by economic sustainability than by social or environmental sustainability, so efforts by policymakers and stakeholders are needed.
[91]	Digitalization and use of smart technologies (IoT, robots, AI, blockchain) in agriculture enable transition of the sector to sustainability in all its three forms: economic, social, and environmental.

Table 4. Main concluding remarks in the reviewed papers related to other performances including safety, productivity, risk management, and resilience during crises. (Source: created by authors).

Source	Research Outcome from Concluding Remarks in a Single Statement (Focus of the Digitalization Concept and Main Problem/s Addressed)
[92]	A blockchain-based framework (Food Safety Quick Response Block, FoodSQRBlock) using QR codes can be successful.
[93]	Food safety, product quality, and associated economic benefits in the dairy industry can be achieved through technological innovation and introducing FSCM practices into lean and green initiatives.
[94]	Blockchain, in the context of e-agriculture, has potential for reshaping the entire sector and helping to resolve the food crisis.
[95]	Sensor-based mobile application technologies for monitoring tracking information and storage conditions of agri-food products are useful in real-operation contexts.
[57]	Wireless sensor networks, cloud computing, IoT, image processing, convolutional neural networks, and remote sensing can improve coffee supply chains.
[96]	Digitalization has disrupted food distributor models; E-commerce models and IoT are essential factors causing retailers to innovate their business models.
[97]	Blockchain-based ASCM can help restrict opportunism in agri-food chains by facilitating management of uncertainty and asset specificity.
[98]	Digital technologies alter agricultural supply chains and offer new ways to create value.
[99]	Competitive advantages can be achieved using ICT solutions for widening and maintaining relations through more effective information flow with partners and consumers.

Table 4. *Cont.*

Source	Research Outcome from Concluding Remarks in a Single Statement (Focus of the Digitalization Concept and Main Problem/s Addressed)
[60]	IoT, blockchain, and other digital technologies have enabling features in food supply chain quality management (FSCQM) and associated challenges.
[100]	Use of blockchain technologies in cooperatives has significant societal impacts in terms of improving milk quality, animal welfare, and milk safety, traceability and transparency.
[48]	The agro-food sector is among the sectors positively impacted by blockchain.
[49]	Technological integrations of blockchain and IoT provide solutions for data security and performance issues in precision agriculture.
[50]	IoT can be a means to optimize supply chains in agriculture.
[42]	The supply chain provenance system for Industry 4.0 in the food sector can be improved using IoT, blockchain, and advanced deep learning.
[101]	Digital supply chain has a significant role in operational performance along the supply chain in terms of quality, productivity, and cost reduction.
[102]	Blockchain technology has high potential for improving supply chains in emerging (Russia) and developed (Germany) economies.
[103]	Blockchain application benefits business performance and adds value for society in the long-term.
[52]	Blockchain is effective in improving food supply chains and has potential for post COVID-19 operations.

However, due to conceptual interactions in performance standards along the food supply chains and difficulty in setting clear boundaries between performance objectives, there were overlaps of focus areas. Moreover, many papers discussed more than one performance issue. Therefore, the organization of concluding remarks by the main area of applications in Tables 2–4 are simply to highlight how digitalization served the different key performance areas of the food system.

Table 3 presents the sustainability related concluding remarks. As can be observed from Table 3, the reviewed literature showed that food system digitalization has a paramount contribution in achieving sustainability targets along the food supply chains. The concluding remarks from reviewed articles revealed that the use of digital technologies in food systems are helping to achieve the social, economic, and environmental sustainability targets. The results in Table 3, suggest the use of digital technologies along the food chain enables to achieve not only the sustainability targets but also the overall food security and safety targets.

Table 4 reports the main concluding remarks of the reviewed articles, which show diversified targets addressed through food system digitalization along the agro-food supply chains. The results in Table 4 revealed that digitalization of the food system helped in improving productivity, product quality, safety, and encouraged business model innovations. Moreover, the review result in Table 4 showed that the use of digital technologies enabled to manage opportunism, uncertainty and risks, reduce costs along the food chains, enable the food system to remain resilient during crises such as the COVID-19 pandemic, and achieve competitive advantages.

In general, the papers covered very broad areas of application of digital technologies or concepts in the food system and described diverse solutions to the complex problems of the food system. Digitalization of the food system was the main solution proposed to solve diverse problems related to food traceability, safety and quality, risk management, productivity, profitability, and so on. This was seen as enabling transformation towards healthier, more sustainable, and more inclusive food systems. Overall, the review showed that digitalization of the food system has untapped potential that could assist in the transition towards an economically, socially, and environmentally sustainable food system that remains resilient during crises (such as the COVID-19 pandemic). However, the papers also pointed out complexities and challenges associated with digitalization of the food system, as discussed further in Section 3.5.

3.3. Food Commodities with High Uptake of Digitalization

The 76 papers reviewed covered either specific food commodities or general food systems (Figure 5). Most papers discussed digitalization of the food system without referring to specific food commodities, i.e., most discussed the application of digital technologies in the general food system. Among the specific food commodities covered, beef/meat, dairy, wheat, fish were most frequently studied for the application of digitalization (Figure 5). The results confirmed the applicability of digitalization for different food commodities.

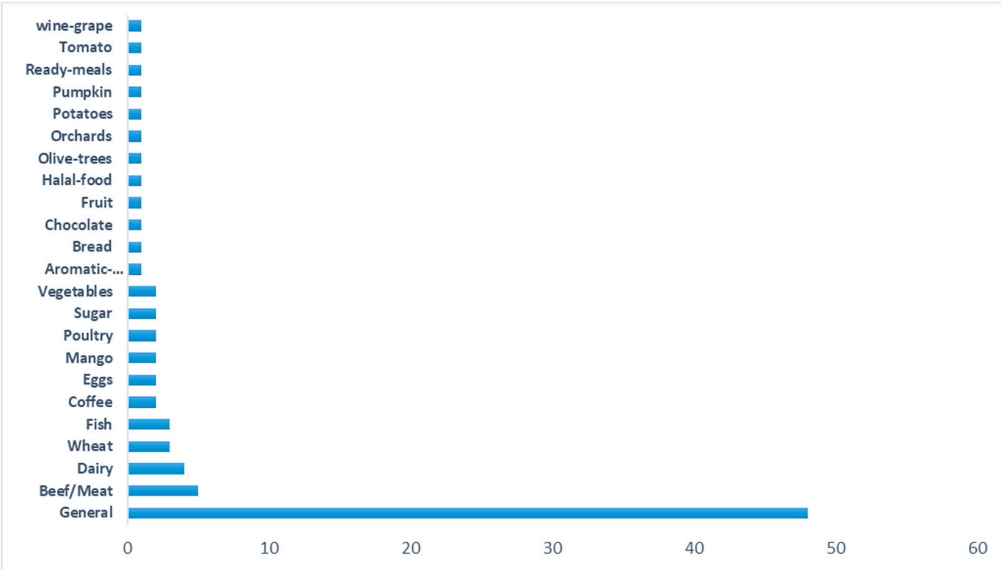

Figure 5. Food commodities studied and frequency of occurrence in the reviewed papers. (Source: created by authors).

3.4. Global Distribution of Digital Applications in the Food System and of Related Scientific Work

From the selected journal articles, the dominant applications of digital technologies to the food system and the scientific basis by country/region were extracted using the country/region studied (Figure 6) and author affiliations by country/region (Figure 7). If multiple authors from different countries were listed in a reviewed paper, all these countries were counted within the frequency values, but if the authors were from the same country that country was counted only once per paper. Similarly, when a paper focused on cases of more than one country, all the countries in the list were counted within the frequency values. More than half of the papers reviewed were general and did not study a particular country (Figure 6). The remaining papers studied cases, mostly in European countries, Asia, and USA. Only two papers studied South American cases (Brazil and Colombia, one case each) and no case paper focused on any country in Africa. From this, it can be deduced that digitalization of the food system can be applied to all food commodities. It can also be deduced that digitalization of the food system is less well advanced in developing countries.

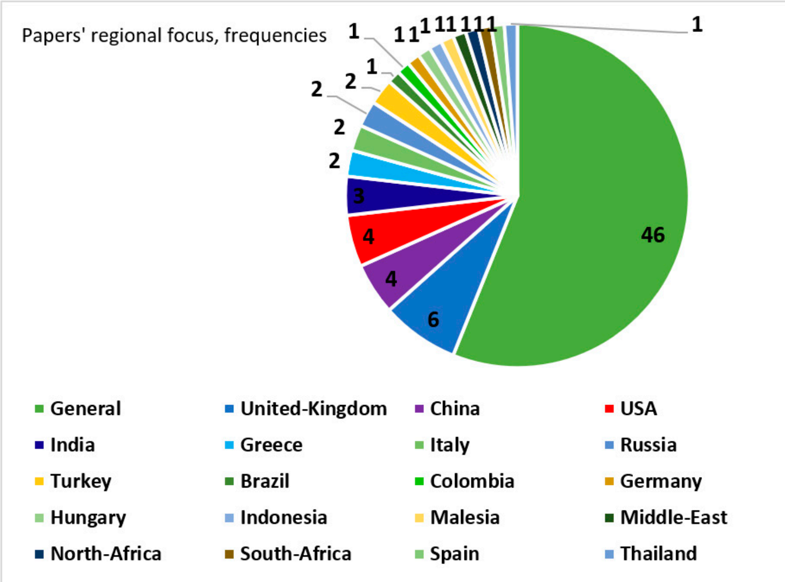

Figure 6. Frequency with which the reviewed papers focused on different countries. (Source: created by authors).

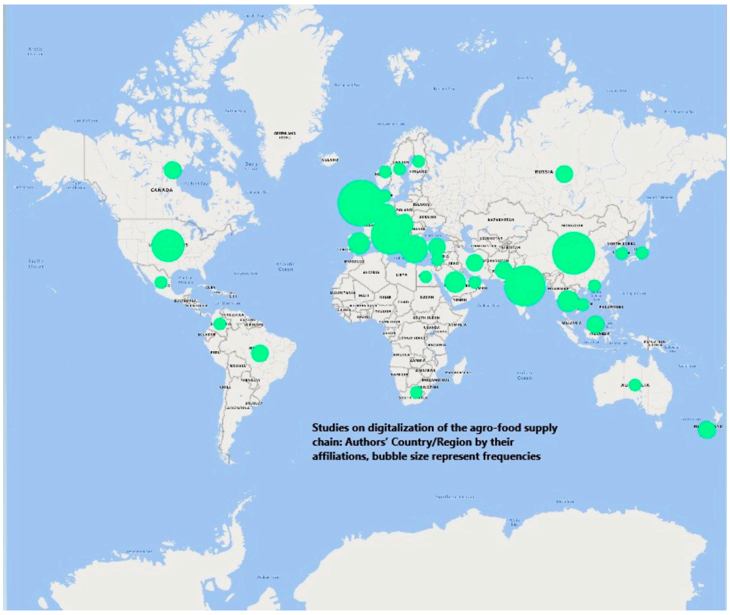

Figure 7. Country/Continent of affiliation of authors of the reviewed papers (bubble size represents frequency). (Source: created by authors).

The global distribution of digital applications to the food system based on author country of affiliation, as shown in Figure 7 (bubble size represents frequency), indicated that Europe as a continent and the United Kingdom (UK) as a country are leading the scientific discussion on digitalization of the food system. China, India, Italy, USA, and Greece were also among the top counties in which food system digitalization was the focus of scientific discussion. Concerning the continental affiliation of authors, Europe, Asia, and USA led the scientific work on digitalization of the food system, while Africa and South America were represented to a very limited degree (Figure 7).

3.5. Challenges in Digitalization of the Food System

Some of the papers reviewed identified challenges to the application of digital technologies to the food system. For organizational purposes, these challenges were classified into five categories, relating to: infrastructure and cost; knowledge, skill, and reputation; law and regulations; the nature of the technologies; and the nature of the food system. There were risks of overlap in this categorization, but it was informative for the preparedness of all stakeholders dealing with digitalization of the food system. The uncategorized list of challenges extracted from the papers reviewed is provided in Appendix B to this paper.

3.5.1. Challenges Related to Infrastructure and Cost

The papers reviewed reported very substantial challenges to digitalization of the food system in terms of infrastructure and cost. Knowledge of these challenges provides insights into the preparedness of practitioners and can serve as input for researchers and inventors developing cost-effective technologies. The infrastructure-cost challenges mentioned included challenges relating to hardware and software, such as the required equipment, storage capacity, rapid detection sensors, and other facilities, which need to be resilient to the harsh agro-food supply chain environment. Poor infrastructure and internet connection in rural (remote) areas, lack of financial resources, high costs of transferring large amounts of data to the cloud, unsustainable energy expenses required for computing power, and high costs of the technologies and of infrastructure development were other challenges identified as threats to the sustainability of digitalization of the food system. It was frequently pointed out that all stakeholders need to work hand-in-hand to solve these challenges [41,50,59–61,91,102–104].

3.5.2. Challenges Related to Required Knowledge, Skill, and Reputation

Although Industry 4.0 is well-advanced in the food system, with the potential for the digital transformation of agro-food chains, the papers reviewed identified significant gaps related to knowledge and skill needed for practical implementation. These gaps in knowledge and skill, combined with other challenges, were seen as threatening the reputation of digitalization efforts, with negative impacts on trust in the system and each other among parties along the food chains. The papers identified a significant number of challenges within this category, including lack of deeper understanding, knowledge, expertise, and technical skills; limited understanding of researchers and practitioners on the technical detail and functions of the systems; and lack of familiarity with the technology among farmers and other stakeholders. Other challenges mentioned concerned consumers' user interface and digital mindset, competencies and involvement; lack of availability of skilled human resources in agro-food enterprises (particularly SMEs); lack of awareness about the technology in the sector, and lack of proper training platforms for educating non-specialized people. Some papers identified challenges to the reputation of the system due to fear of unethical behavior and of decentralization, challenges in accepting the new normal, as digitalization could change the way people work, and consumer misunderstanding and lack of trust in the technology [41,42,44,47,53,54,61,70,81,91,94,96,103].

3.5.3. Challenges Related to Law and Regulations

Regardless of the benefits it could bring to the food system, there are legal issues associated with digital applications that stakeholders need to keep in mind. Digitalization of the food system poses challenges in terms of the law and regulations as it does in other business sectors. Knowledge of legal and regulation-related challenges in digitalization of the food system would help policymakers and stakeholders to customize legal procedures and customs in a manner that reduces the risk to partners along the food chain in terms of confidentiality, privacy, security, and any other business interest. As in the other categories, the papers reviewed listed a number of challenges related to law and regulations in digitalization of the food system, including challenges related to data ownership, privacy and security; security challenges through external attacks; authenticity, confidentiality, and privacy of the stakeholders involved; global food value chains and cross-border law related to data cryptocurrencies; lack of regulation; and lack of clear data governance [42,46,50,53,59,61,103].

3.5.4. Challenges Related to the Nature of the Technologies

Some challenges arise because of the new, complex, and intrinsic characteristics of the digital technologies. Understanding these challenges will help inventors and researchers to develop user-friendly technologies. The reviewed papers identified many challenges within this category with high emphasis on problems relating to the data generated by digitalization of the food system. Quality challenges with big data, questionability of sustainable integration of the data, challenges in standardization of the data, and possibilities for raw data manipulation were among the data-related challenges identified [44,45,60,74,80]. The openness of the platform, technological complexities (non-friendly), difficulty in implementation in small and medium agro-food enterprises, difficulties in coordinating with partners of different sizes (agro-business size compatibility), and compatibility and complementarities of the technologies with existing technologies were other challenges mentioned in this category [44,64,94,104].

3.5.5. Challenges Related to the Nature of the Food System

Some challenges of digitalization of the food system identified by the papers reviewed related to the nature of the food system itself, where "food system" refers to "the sum of actors and interactions along the food value chain—from input supply and production of crops, livestock, fish, and other agricultural commodities to transportation, processing, retailing, wholesaling, and preparation of foods to consumption and disposal" as defined by the International Food Policy Research Institute [105]. The harsh-agro-food supply chain environment, the complex and multi-actor interactions along food chains, and conflicts of interests complicate digitalization of the food system. Other challenges cited in this category were transformation of products at multiple stages of food chains; heterogeneous roles of the large number of businesses involved along food chains; difficulty in data cryptocurrencies and interoperability for food supply chains that cross national borders (global food supply chains); challenges related to food supply chain network structures; decision-making models along food chains; low collaboration and trust and unclear behavioral intentions among key stakeholders; and difficulties in forming interconnections between different sub-systems along food chains [42,47,50,60,74,80].

4. Summary and Implications

The papers reviewed here indicated that the use of digital technologies such as blockchain, IoT, big-data analytics, AI, and ICT can act as enablers for sustainable transformation of the food system. Most of the papers reviewed (Table 2, Figure 4) mentioned the benefits of digitalization of the food system in achieving traceability, an important issue that provides consumers with information about the origin of the food products. This includes information about where, when, and how a product is produced, its nutritional content, transformation/value addition steps along the food chain, the nature of the food, its shelf-life, and the ability to track its route through the food chain. As traceability is associated with critical consumption characteristics of food, such as safety, quality, and nutritional content, it is an important concept for all stakeholders in the food industry. Therefore, achieving food traceability could provide a competitive advantage for agro-food supply chain actors. It could also provide a number of other benefits, including the ability to predict food perishability and manage food losses/waste; reduced costs (e.g., inventory carrying costs) and higher efficiency; good customer relationships and marketability as a result of confidence in the food; and minimized legal liability associated with risks related to food hazards from consumption of contaminated food and/or wrongly labeled food products. Note that legal liability may arise not only from the sale of contaminated food but also from the sale of wrongly labeled food items. For instance, horse meat labeled as beef in the food scandal of 2013 [106], which had catastrophic economic implications for food chain actors in the UK and across Europe, arose from fraudulent activity in the food chain, which indicates how deception in food chains and lack of appropriate tracking of foodstuffs can create trouble for the whole food system. Central to food system traceability is food system information collection, processing, and real-time interchange. The papers reviewed reported particular benefits from the use of digital technologies such as blockchain, IoT, and ICT in this regard.

Besides enabling traceability, use of the digital technologies in the food system was reported to provide a way forward for a sustainable food system (Table 3, Figure 4). Sustainable food system is defined by the United Nations Food and Agriculture Organization as a "food system that delivers food security and nutrition for all in such a way that the economic, social, and environmental bases to generate food security and nutrition for the future generations are not compromised" [107]. According to that definition, a food system is sustainable when it fulfills three sustainability requirements: economic sustainability (the food system is profitable for actors throughout); social sustainability (the food system has broad-based benefits for society); and environmental sustainability (the food system has positive or neutral impacts on the natural environment). Digitalization of the food system was also seen as very valuable in improving some other key performance parameters along the food chain, such as productivity, profitability, quality and safety, resilience to crisis situations such as the COVID-19 pandemic, and profitability, and in enabling food supply chain management in risk management, coordination, and trustful networking (Table 4, Figure 4). Some of the papers reviewed [58,104,108–111] reported the potential of digitalization in reducing food waste, a critical issue in sustainable food systems transition and in the United Nations Sustainable Development Goals (SDG 12.3). The papers reviewed demonstrated the benefit of digitalization of the food system for the overall food system and for specific food commodities. However, the global distribution of digitalization applications and of related scientific research was concentrated in developed countries in Europe, Asia, and USA. The papers identified different challenges hindering digitalization of the food system in practice. To assist understanding and increase preparedness among policymakers, researchers, and inventors, these challenges were categorized into five groups, relating to infrastructure and cost; knowledge, skills, and reputation; law and regulations; the nature of the technologies; and the nature of the food system.

There are two main implications of this review. First, digitalization of the food system is an important and timely issue to consider in the transition towards a food system that can deliver universally accessible, affordable, and healthy food and can remain sustainable and resilient. Second, digitalization is well-advanced in the food system, but its application and scientific work are mainly concentrated to developed countries. Even in the developed countries, there are still many challenges that need the attention of all stakeholders in the food system. Thus, the use of digital technologies in the food system has untapped potential. However, the challenges of digitalization of the food system is a critical assignment to deal with for food supply chain managers, food chain actors, governments, and international organizations dealing with food and food policies. Targeted policies and regulations, support for infrastructure development, subsidization of digital development in food chain facilities, and education and training to develop human capital could facilitate fuller digitalization of the food system.

Author Contributions: The contribution of T.K.A. and G.G. in this paper is conceptualization, 85%, 15%; methodology, 80%, 20%; software, 90%, 10%; analysis, 80%, 20%; data, 80%, 20%; writing—original draft preparation, 90%, 10%; writing—review and editing, 80%, 20%; overall, 84%, 16%, respectively. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors would like to thank the editor and anonymous reviewers for their valuable comments regarding this paper, which helped to improve the quality significantly from its initial submission.

Conflicts of Interest: We declare that there is no conflict of interest related to this paper.

Appendix A

Table A1. The main problem addressed by digital technology or concepts in the papers reviewed (repetitions represent multiple papers).

Traceability	Transparency Accountability Auditability Smart-contract Traceability Traceability Traceability Traceability Visibility ProvenanceDisintermediation Smart-contracts Traceability Traceability Safety-management Transparency Auditability Traceability Secure-identification Traceability Real-time-tracking Transportation Traceability Transparency Traceability Traceability Traceability Quality-control Ensuring-safety-of-food Traceability Traceability Traceability Traceability Traceability Security-in-agri-food-system Traceability Traceability Trust Cyber-risk-management-food supply-chain Safety Security Transparency	Sustainability	sustainable-performance sustainability produce-more-food-more-sustainably achieve-UN-Sustainable-Development-Goals agro-food-sustainability-transition sustainable-food-systems sustainable-food-supply-chain sustainable-food-supply-chain-management sustainability optimizing-energy-consumption sustainable-supply-chain sustainability resource-efficiency Sustainable-food-supply-chain sustainable-food-supply-chains sustainable-financing-stream-for-food chains sustainability-performance-of-food-supply-chain social-sustainability sustainable-agri-food-systems
		Other performance issues	productivity supply-chain-performance supply-chain-performance data-accessibility precision-agriculture link-consumers-with-farmers smart-short-food-supply-chain post-COVID-19 crisis response Uncertainty-management yield-growth-prediction matching-food-production-to-market-needs efficiency effectiveness post-COVID-19-crisis operational-performance quality productivity cost-reduction quality-management smart-agriculture
Other food supply chain management issues	Supply-chain-management Supply-chain-management Supply-chain-management Distribution-management Risk-management Decision-making Agri-food-supply-chain-management Network-management Supply-chain-management Food-supply-chain-management Agri-food-supply-chain-management Restrict-opportunism Coordination Supply-chain-management Quality-decision-making Resilient-regional-food-supply-chains	Reducing food waste/loss	waste/loss reduce-food-waste/loss reduce-food-food-waste/loss reduce food waste/loss reduce-food waste/loss reduce-food-waste/loss reduce-food-waste/loss reduce-food-waste/loss

Appendix B

Table A2. The main challenges to digitalization of the food system identified in the papers.

Source	Main Challenge Identified
[41]	Difficulties relating to cost and profitability, technical knowledge or expertise, suitability to local conditions, complementary technologies.
[42]	A demand for high level-expertise, which is difficult for SME organizations, lack of awareness about blockchain technology, lack of proper training platforms for educating non-specialized people, cryptocurrencies (many countries have banned cryptocurrency at state level), ensuring farm owners share the right information on the network.
[63]	Difficulties in practical implementation and the reputation of the system.
[64]	The complexity of implementation of IoT with agro-food small and medium enterprises (SMEs).
[53]	Lack of deeper understanding of blockchain, technology; raw data manipulation, difficulties in getting all stakeholders on board, and deficiency of regulations.
[70]	As it is new, the technology may lack consumer understanding and trust.
[71]	The decision to change or implement traceability technologies in the food supply chain requires comprehensive analysis.
[54]	Limited understanding of researchers and practitioners on the technical detail and functions for food traceability management.
[74]	Heterogeneity of participating actors, stakeholders, and business models; different levels of confidentiality; lack of interoperability between systems; lack of clear data governance.
[59]	Technical and behavioral challenges and limitations in adoption of blockchain technology, such as storage capacity, the security and privacy of blockchain, high investment costs in adoption, less collaboration and trust among key stakeholders, and behavioral intentions among the chain actors.
[61]	Internet connectivity, data privacy and security, economic sustainability (cost effectiveness),consumer and stakeholder acceptance.
[80]	Challenges related to supply chain network structure, data collection, decision-making models, and implementation.
[44]	Data ownership, privacy, and security issues; quality of big data, availability of skilled human resources for big-data analysis; sustainable integration of data; and openness of the platforms.
[45]	Data security, infrastructure, standardization of data, device interoperability.
[46]	Data privacy and security.
[47]	Low stakeholder technological knowledge, several transformations of the products at multiple stages of food chains, heterogeneous roles of the large number of businesses involved along food chains; difficulty of data interchange/interoperability for food supply chains that cross national borders (global food supply chains).
[81]	Problems with accepting the new normal: the biggest challenge to digitization of agriculture is that digitization and innovation will change actor identity, hence a need to change the way of working.
[85]	There is more focus in the literature on the environmental aspect of sustainability and less attention is paid to the socio-economic aspect.
[55]	Management challenges.
[91]	Poor infrastructure and internet connection in rural areas, low technological level on farms.
[94]	Complexity, new to the sector, farmer and other stakeholder unfamiliarity with the technology.
[60]	Cost of the technologies, difficulties in handling a large amount of data generated by IoT, including the hardware cost and saturated communication channels (bandwidth); information security of data collected by IoT devices; lack of standardization in IoT systems can lead to difficult interconnections between different systems, platforms and standards; the need for rapid detection sensors can withstand the harsh agro-food environment.
[50]	Hardware & software challenges: requirement for equipment that is resistant to harsh environmental conditions, such as high solar radiation, extreme temperatures, rain or high humidity, strong winds, vibrations, and other dangers capable of destroying electronic circuits; organizational challenges & interoperability: high cost to transfer huge amounts of data to the cloud, both in terms of money and latency; networking challenges: harsh environment caused low wireless link quality; security challenges: security against external attacks, of all kinds, on the data transferred to ensure the security, authenticity, confidentiality and privacy of the stakeholders involved in the network.

Table A2. *Cont.*

Source	Main Challenge Identified
[102]	Difficulty with high investment and availability of technological and human resources.
[103]	Lack of resources such as financial, knowledge, expertise, technical (e.g., internet connection in remote areas) requirements; low digital skills and great technical complexity; lack of regulation; unsustainable energy expenses needed in computing power; social resistance due to: (i) unethical behaviors, (ii) fear of decentralization.
[104]	Barriers to the integration and usage of digital technologies, including difficulties coordinating partners that differ in size; digital mindset, resources, competencies and involvement, risk propensity and risk awareness.
[112]	Limited understanding that further impedes adoption by stakeholders, particularly farmers.

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