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Review

Digitalization in Food Supply Chains: A Bibliometric Review and Key-Route Main Path Analysis

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Abstract: Technological advances such as blockchain, artificial intelligence, big data, social media, and geographic information systems represent a building block of the digital transformation that supports the resilience of the food supply chain (FSC) and increases its efficiency. This paper reviews the literature surrounding digitalization in FSCs. A bibliometric and key-route main path analysis was carried out to objectively and analytically uncover the knowledge development in digitalization within the context of sustainable FSCs. The research began with the selection of 2140 articles published over nearly five decades. Then, the articles were examined according to several bibliometric metrics such as year of publication, countries, institutions, sources, authors, and keywords frequency. A keyword co-occurrence network was generated to cluster the relevant literature. Findings of the review and bibliometric analysis indicate that research at the intersection of technology and the FSC has gained substantial interest from scholars. On the basis of keyword co-occurrence network, the literature is focused on the role of information communication technology for agriculture and food security, food waste and circular economy, and the merge of the Internet of Things and blockchain in the FSC. The analysis of the key-route main path uncovers three critical periods marking the development of technology-enabled FSCs. The study offers scholars a better understanding of digitalization within the agri-food industry and the current knowledge gaps for future research. Practitioners may find the review useful to remain ahead of the latest discussions of technology-enabled FSCs. To the authors' best knowledge, the current study is one of the few endeavors to explore technology-enabled FSCs using a comprehensive sample of journal articles published during the past five decades.

Keywords: agri-food; food supply chain; blockchain; IoT; big data; sustainability; food security; COVID-19; food safety; digitalization

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1. Introduction

The food supply chain (FSC) plays a critical role in the world economy [1] and has been one of the crucial pillars of human civilization throughout history [2,3]. It refers to the chain starting from the raw materials in agriculture to the process of production and product distribution and the linkages between them [4,5]. From the definition, it appears that the FSC encompasses all the stages regarding the supply, production, and consumption of a food product. Scholars have voiced the need to transform the traditional FSC for several

reasons. The supply chain has to feed 9.7 billion in 2050 compared with 7.8 billion today [6]. This enormous increase should be addressed in all stages of the process. Furthermore, as agriculture is the most prominent source of food globally, water consumption is expected to rise dramatically and pose a sustainability issue [3,7,8]. Greenhouse gas emissions, climate change, the increasing consumption of fertilizers and pesticides, and other resources, as well as pollution caused by production, distribution, and logistics stages are among other environmentally damaging consequences of such an increase [9–11]. In addition, there are debates about the safety, quality, and security of food products which call for enhancements in traceability and transparency of the FSC [12,13]. Additionally, the perishable nature of food products and food loss throughout the FSC compels academia and industry to improve real-time monitoring and traceability capabilities [14,15].

A promising solution to the abovementioned challenges is incorporating cutting-edge technologies. The digitalization of the FSC has been considered a necessity to achieve sustainable competitive advantage and decrease value chain risks [16–19]. Various scholars have investigated various technologies to contribute to the digital transformation of the FSC. Incorporating the Internet of Things (IoT) [20–24], blockchain technology [25–27], big data [20,28,29], wireless sensor networks (WSN) [30,31], artificial intelligence (AI) techniques [32–36], computing technologies [28,37–39], geospatial technologies [40], radio frequency identification (RFID) [26,41], and remote sensing technologies such as drones [42,43] are among these innovative endeavors.

Since research on the technology-enabled FSC has witnessed considerable growth during the last two decades, the need for structured reviews based on quantitative methodologies is urgent to summarize the field and reveal the conceptual structure of the knowledge domain [44]. In the extant literature, the efforts mostly have been placed on examining and summarizing the intersection of a specific technology and a limited part of the supply chain, such as: Industry 4.0 technologies and agriculture [45], WSN and agriculture intersection [46], IoT and FSC dynamics [47,48]; IoT and food safety [49]; IoT, data analytics, and agriculture [7]; distributed ledger technology and the FSC [50]; blockchain and FSC traceability [51]; IoT, big data, AI and FSC domain [52]; IoT and quality management in the FSC [48]; blockchain and agri-food industry or FSCs [53,54]; and big data and food safety [55]. Although all these endeavors have provided fruitful insights into the opportunities and challenges of new technologies in the food sector, none has investigated the entire field of technology-enabled FSCs from a holistic perspective. A few studies summarized the technology-enabled supply chain domain, including [56], who reviewed the fresh fruit and vegetables supply chain literature from the resource-based view perspective and identified several potential opportunities and weaknesses of ICT technologies as firm resources. Similarly, Ref. [57] surveyed economic, environmental, social, functional, and technological impacts and challenges of four important agri-food 4.0 technologies, namely IoT, big data, AI, and blockchain in FSC application. These studies also provide an increased understanding; nevertheless, none investigated the field based on a quantitative structured methodology such as bibliometrics to visualize the knowledge domain and reveal the big picture.

To fill this gap, we conduct a bibliometric and key-route analysis to examine the knowledge surrounding the technology-enabled FSC. By doing so, this study provides academics and business practitioners significant insights into the trajectories and evolution of the technology-enabled FSC knowledge domain. Various research paradigms and foci discussed in the field from different perspectives could be better identified. The study also reveals the most influential papers, authors, sources, and countries. By identifying and presenting the current status, research gaps, future research directions of technology-enabled FSCs, this study can contribute to academia and industry. In our journey, we are guided by the following research questions:

- What are the dynamics between technology and the FSC in the reviewed publications?
- What technologies are being adopted to improve the FSC?
- How are various technologies being adopted in the FSC?

- What are the current research gaps at the intersection of technology and the FSC?

The remainder of the paper is structured as follows: Section 2 presents the research methodology, including the bibliometric approach, the key-route main path method, and the data gathering strategy; Section 3 discusses the main findings of descriptive analysis; followed by the results of the keywords co-occurrence network and key-route main path analysis in Section 4; finally, Section 5 concludes and provides research implications, limitations, and future directions.

2. Research Methodology

2.1. Bibliometric Method

Since the primary objective of this review is to examine the current knowledge on technology-enabled FSCs, we conducted a bibliometric and key-route main path analysis. Unlike traditional reviews, bibliometric reviews represent a systematic analytical tool that helps researchers determine the most influential authors, their affiliations, the keywords they selected, and the interrelationships between their works [58]. The use of bibliometrics is suitable when investigating the current status of a particular research field using various indicators, including influential authors, journals, countries, and academic institutions. With the support of bibliometrics, researchers would be able to identify levels of research collaborations among authors, institutions, and countries. The bibliometric approach ensures a transparent, objective, and systematic representation of research [59]. This research method has been commonly applied in the prior literature to analyze a high volume of publications in diverse fields and domains such as green supply chain management [60], sustainability [61,62], blockchain technology [63,64], and halal food [65–67].

This review draws on bibliometric analysis as the appropriate tool to investigate the existing knowledge based on which the interplay between technologies and sustainable FSCs is founded. As part of this focus, we performed a keyword co-occurrence network analysis to gain an in-depth understanding of this topic. A keyword co-occurrence network analysis reveals that author-supplied keywords co-occur, and it depicts the relationships between them. According to [68], this network analysis enables researchers to identify research topics and understand the transition of research frontiers in a specific scientific field. In the keyword co-occurrence network, two keywords are closely related if they appear in the same publications more frequently. By producing the keyword co-occurrence network, we aspired to analyze the core content from the used keywords and assess the research structure at the intersection of technologies and sustainable FSCs. The visual tool chosen for generating this network was VOSviewer due to its high compatibility with the BibExcel software. Density was used to measure the strength of association between keywords [69]. In VOSviewer, VOS mapping allows researchers to obtain a map of nodes for keywords and the distance between each pair of keywords based on density [70]. The general idea of the algorithm is to minimize the weighted sum of squared Euclidean distance between each couple of keywords in an iterative process [71]. Accordingly, the nearer the distance between two keywords, the higher is the density value.

2.2. Key-Route Main Path Analysis

To supplement the keyword co-occurrence network, we conducted a key-route main path analysis to examine the knowledge diffusion routes and understand the historical development of technology-enabled sustainable FSCs. In a citation-link network, as shown in Figure 1, the search path count (SPC) of a link constitutes the total number of times that a link is traversed if one exhausts the search from all node sources (i.e., nodes that are only cited while referring to no other nodes) to all sink nodes (i.e., those that are not cited by other nodes but only cite other nodes) in the citation network. For example, the SCP of the link C-D is four because only four paths pass through this link, namely, A-C-D-G, A-C-D-H, B-C-D-G, and B-C-D-H. However, the search path link count (SPLC) is another way of measuring the importance of a link, consisting of the number of times one link is traversed if one runs through all possible paths from all earlier nodes to all sink nodes [72]. For

example, the SPLC of the link C-D is six because six paths pass through this link (including the starting node C), namely, A-C-D-G, A-C-D-H, B-C-D-G, B-C-D-H, C-D-G, and C-D-H. Because intermediate nodes (e.g., C) pass and generate knowledge [73], the SPLC is chosen to weight the citation network and reflect the current knowledge diffusion situation.

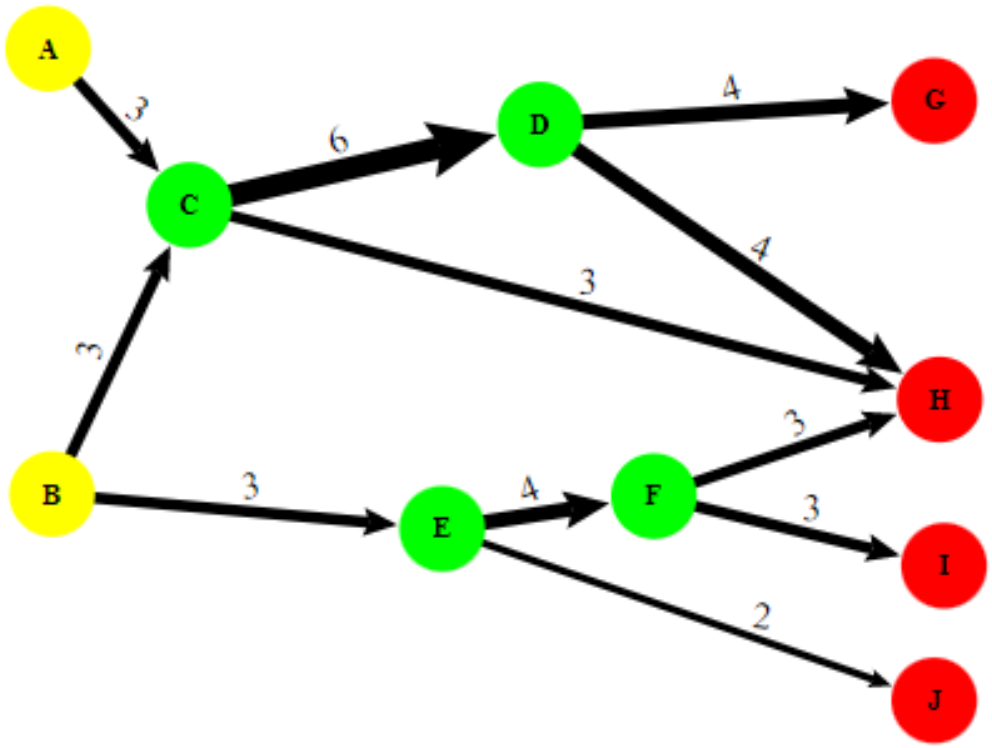


Figure 1. A typical citation network weighted with SPLC values.

According to [74], the key-route search process starts with the link with the highest traversal weight and then searches forward from the end node of the link until a sink node is reached, then searches backwards from the beginning node of the link until a source is reached. The resulting path-fragments are coupled together to construct the key-route main path. The more key-routes are chosen, the more details and information about the main path are revealed. Therefore, the key-route main path is preferred in this study to capture prior knowledge and most significant links in the main path [74].

To simplify understanding, the key-route main path generated from Figure 1 is presented in Figure 2. Since the link C-D has the largest SPLC value, it is chosen as the citation link, which plays an important role in the knowledge diffusion procedure. When searching forward and backward from the link C-D, the key-route main path is obtained and shown in Figure 2.

2.3. Data Collection

For our study, data from the Scopus database was retrieved. Scopus represents a world-leading repository widely recognized for its comprehensive coverage and reliable content, containing a large number of publications published in journals provided by premier publishers such as Elsevier, EmeraldInsight, Springer, and Taylor and Francis [75,76]. The search string used was the following: ("food" OR "agri-product" OR "agri-food" OR "agriculture") AND ("Sustainab*" OR "environ*" OR "Green" OR "eco*" OR "Social" OR "Societal" OR "CSR") AND ("Supply chain" OR "Value Chain" OR "Logistics") AND ("Digi*" OR "Information Syst*" OR "techno*" OR "big data" OR "data analy*" OR "Business Intelligence" OR "Artificial Intelligence" OR "Social Media" OR "Internet of Things" OR "Blockchain"). The search was carried out in the title, abstract, and keyword fields.

To maintain the academic nature and high quality of the literature, the search was only limited to peer-reviewed English-speaking journal articles. The authors screened the titles and abstracts of these articles, excluding all publications with missing bibliometric data (e.g., abstracts, keywords). As a result, 2140 documents were retrieved from Scopus in .txt and CSV. formats for the final analysis using the visual tools VOSviewer and Pajek.

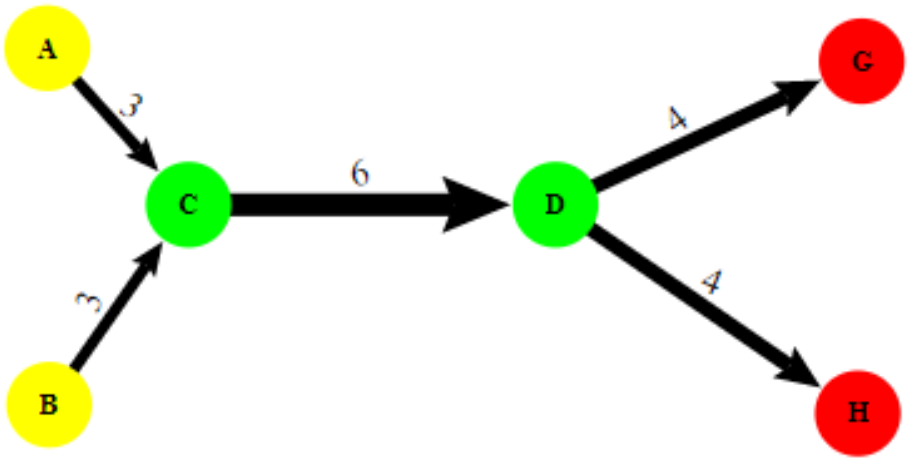


Figure 2. The key-route main path from the typical citation network.

3. Results of the Descriptive Statistics

3.1. Publications by Year

Figure 3 shows the annual distribution of 2140 journal articles, showing a consistently growing trend since 1975. In the first two decades (1975–1995), the literature appears scarce, with less than four papers each year. These two decades may be referred to as the initial stage in research on technology-enabled FSCs. The following two decades (1996–2015) witnessed increased attention toward the topic, as demonstrated by the slight increase in the number of publications. This stage can be designated the initial growth stage. The subsequent five years (2016–2021) are featured by a rapid increase in research interest in the topic of technology-enabled FSCs. This stage can be named the exponential growth stage since it observes the most significant growth rate during the study period.

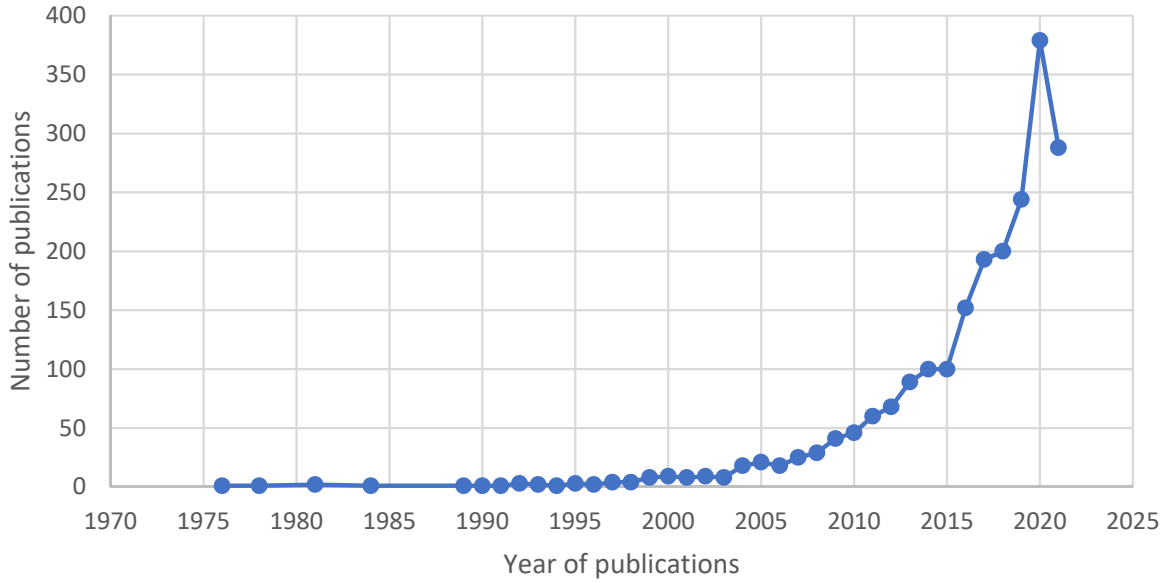


Figure 3. The year-wise distribution of publications.

3.2. Publications by Country

Table 1 shows the distribution of publications according to countries. As can be seen, the highest number of publications (509) originated in the USA, followed by the United Kingdom (270), China (179), Italy (166), and India (152). Summarizing, research on technology-enabled FSCs has been carried out worldwide, even though there is a high concentration of scholarly output in developed countries. North America and Europe contributed significantly to the literature, ranking higher than Asia; meanwhile, North African countries are not included in the list. Although this may call for increasing research cooperation, it should be mentioned that only English-speaking publications were selected for this review.

Table 1. Top 20 contributing countries.

Country	Number of Publications
United States	509
United Kingdom	270
China	179
Italy	166
India	152
Australia	113
Canada	110
Netherlands	106
Germany	100
Spain	84
France	69
Brazil	65
Belgium	56
South Africa	46
Switzerland	46
Greece	43
Sweden	42
Denmark	41
Kenya	40
Malaysia	40

3.3. Publications by Institutions

Table 2 depicts the top 20 academic institutions contributing the most to research pertaining to technology-enabled FSCs. The affiliation with the highest number of publications is Wageningen University and Research with 68 publications, followed by Michigan State University with 25 publications and Universiteit Gent with 19 publications. In general, the list of top 10 productive institutions does not contain institutions located in developing nations. Although research on technology-enabled FSCs disperse worldwide, the low research productivity of academic institutions belonging to developing nations may partially be justified by the insufficient cooperation between countries, specifically between scholars of developing and developed nations. The lack of technological infrastructure and resources may be another reason for the digital gap between these nations.

Table 2. Top 10 most relevant institutions.

Institution	Number of Publications
Wageningen University & Research	68
Michigan State University	25
Universiteit Gent	19
Cornell University	18
Imperial College London	18
University of Minnesota Twin Cities	17
University of Saskatchewan	16
Texas A&M University	16
INRAE	15
Universität Bonn	14
Alma Mater Studiorum Università di Bologna	14

3.4. Publications by Journals

Table 3 shows the top 20 relevant journals publishing articles on technology-enabled FSCs. Overall, these journals published 466 articles, representing 19% of the 2460 publications that were included in our sample. *Journal of Cleaner Production* tops the list with 88 articles. Following closely, *Sustainability* published 85 articles, *PLoS ONE* 29 articles, and *British Food Journal* 25 articles. The journal-wise distribution of the scholarly output reflects the distribution suggested by Bradford's law, which suggests that there is a small group of main journals that account for an important percentage of articles on that discipline or subject [77]. Furthermore, the scope of these journals draws upon several research areas and topics, including sustainability, food science, environmental science, agriculture, and computer science. As a result, articles published in these journals mirror the diversity, richness, and multidisciplinary nature of technology-enabled FSC research.

Table 3. Top 20 most relevant journals.

Journal	Number of Publications
Journal of Cleaner Production	88
Sustainability	85
PLoS ONE	29
British Food Journal	25
International Journal of Environmental Research and Public Health	22
Science of the Total Environment	22
Computers and Electronics in Agriculture	19
Food Policy	16
Biomass and Bioenergy	14
IEEE Access	14
International Journal of Supply Chain Management	14
Journal of Environmental Management	14
Resources Conservation and Recycling	14
Trends in Food Science and Technology	14
Agricultural Systems	13
International Food and Agribusiness Management Review	13
International Journal of Production Economics	13
Renewable and Sustainable Energy Reviews	13
BMC Public Health	12
Nutrients	12

3.5. Most Productive Authors

Table 4 depicts the most prolific authors with five publications or more. According to the data, Hobbs (eight articles) and Mangla (seven articles) dominated the list of publications. Other productive authors include Beulens (six articles), Kamble (six articles), Rahimifard (six articles), and Shah (six articles).

Table 4. Most productive authors with five or more publications.

Author	Number of Publications
Hobbs, J.E.	8
Mangla, S.K.	7
Beulens, A.J.M.	6
Kamble, S.S.	6
Rahimifard, S.	6
Shah, N.	6
Barrangou, R.	5
Engelseth, P.	5
Freidberg, S.	5
Gunasekaran, A.	5
Luthra, S.	5
Mishra, N.	5
Raut, R.D.	5
Reardon, T.	5
Sarkis, J.	5
Singh, A.	5

3.6. Keyword Frequency Analysis

Keyword frequency analysis aims to determine research hotspots and development trends based on the number of occurrences of keywords [78]. Since the keywords are retrieved from the core content of the publication, if a keyword is used constantly in a specific knowledge domain, the topic it conveys can be judged to have received significant attention from scholars and can therefore be considered as a hotspot in the domain [79]. Moreover, the selection of keywords follows specific rules, as keywords are often utilized to; identify research ideas; define the research field; restrict the scope of the investigation; synthesize research; and discuss the methodology or theory employed in a study [78]. As a result, if we analyze keywords based on their frequency and the meanings they reflect, we identify hotspots in particular knowledge domains. Following this approach, we initially extracted the most frequent keywords and carried out a content analysis with regard to digitalization and the FSC. Table 5 shows the 20 most frequent keywords in the selected 2140 publications. Because of increasing consumer awareness and higher resource consumption, food industry stakeholders must achieve sustainable consumption and production by coordinating and optimizing their FSC operations [80]. The integration of sustainability and the FSC is an evolving research area that has given rise to new methods and practices of managing food systems over recent decades [81]. For example, Ref. [82] noted the role of information and communication technologies (ICT) in agricultural production to maximize agricultural yield and support farms to be more productive, thereby increasing food security. Most frequently used keywords include "IoT" and "Blockchain." In recent years, IoT has had great potential for application in the domain of food and agriculture as the technology can facilitate traceability from farm to fork, contribute to food safety, and reduce agricultural inputs and food waste [83]. Several studies emphasize the abilities of IoT to support real-time information collection and sharing, augment FSC sustainability, and reduce issues related to food quality and safety [8,84–86].

Table 5. Top 20 most frequent keywords in technology-enabled FSCs research.

Keyword	Frequency
Sustainability	143
SC (Supply Chain)	116
Agriculture	82
FSC (Food Supply Chain)	81
IoT (Internet of Things)	70
Food Security	67
Blockchain	63
Food Waste	60
SCM (Supply Chain Management)	58
LCA (Lifecycle Assessment)	56
GIS (Geographic Information System)	55
Food Safety	48
Value Chain	47
Innovation	46
Food Industry	46
Traceability	44
Logistics	43
Coronavirus	40
ICT (Information Communication Technologies)	32
Circular Economy	32

Combined with IoT, blockchain can overcome several traceability issues and improve FSC transparency because it is plausible to keep data from chemical analysis in chronological order, thereby eliminating data manipulation and falsification [17]. From the supply chain and logistics perspective, blockchain has been praised for its visibility, immutability of transactions, and its trustworthiness among participating stakeholders [87]. The keyword "GIS" (geographic information systems) appears frequently, implying that the development of GISs brings several opportunities to FSCs as they enable the monitoring and control of crop growth at a very precise level [86]. Furthermore, the trend of digitization in the FSC has been reinforced by the 2020 coronavirus (COVID-19) pandemic [88], which has altered the attitude of food consumers and laid bare several logistical issues in FSCs such as rising food demand, supply disruption, and lack of FSC resilience [89]. Facing the challenges posed by the COVID-19 pandemic, the existing linear systems of production and consumption are deemed unsustainable as finite natural resources are substantially used to produce and distribute foods. For this reason, several scholars have advocated positive outcomes from the implementation of circular economy strategies, including food waste reduction, increased environmental sustainability, and promotion of sustainable and resource-efficient policies [90–92]. Overall, all the keywords listed in Table 5 suggest the practicality of technology-enabled FSCs to optimize operational efficiencies, mitigate disruptions, and ensure sustainability in the agri-food industry.

4. Results from Bibliometric and Key-Route Main Path Analysis

4.1. Keyword Co-Occurrence Network Analysis

The keyword co-occurrence network is used to identify "keywords" that co-occur in at least two publications in a time span [93]. This scientometric method enables to generate clusters that provide a broader view of different research foci in a specific knowledge domain [94]. To obtain the network, we began by extracting all keywords from each publication. We pretreated and harmonized the keywords to maintain consistency. For instance, keywords that are written in full length (e.g., food supply chain, internet of things, big data analytics, information and communication technologies) were abbreviated. The appearance of two keywords within the same publications indicates the association between topics to which they relate [95]. The keyword co-occurrence network analysis helps scholars to detect the core content of the literature and depict the structure of a knowledge

domain. Therefore, to obtain the network, the data were loaded into VOSviewer, and the density-based spatial clustering based on the full counting method was used [96]. Since the suitable number of keywords in the network varies from 200 to 500 [97], a keyword has to occur at least eight times in the selected 2140 publications in order to appear in the network. As a result, five clusters with distinct colors were generated, as shown in Figure 4 and detailed in Table 6. A node constitutes a keyword, and the node size corresponds to the co-occurrence frequency of the keyword. The distance between two keywords in the visualization is determined by density, and the higher this density, the closer is the distance between two nodes [79].

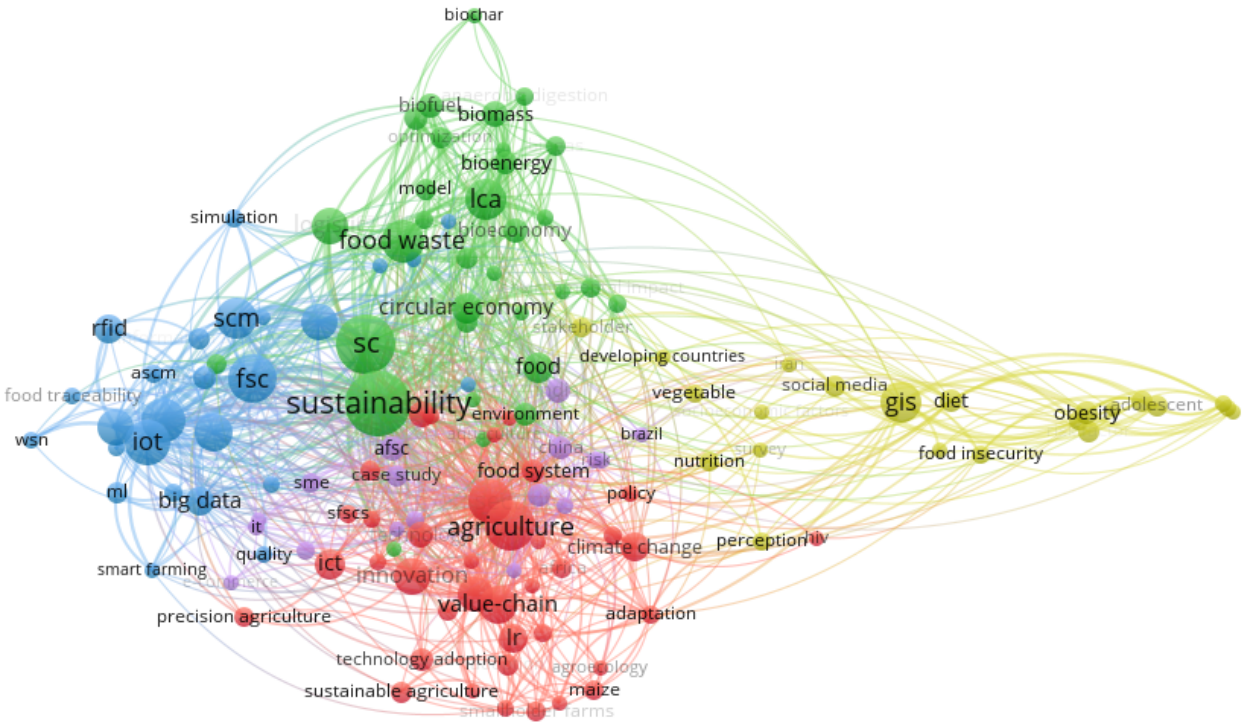


Figure 4. Keyword co-occurrence network.

4.1.1. ICT for Agriculture and Food Security

Table 6 demonstrates that cluster 1 focuses on the contributions of ICT and innovation to food security and sustainable development goals; thus, we labeled it as ICT for agriculture and food security. Examples of the most relevant keywords in this cluster are "agriculture," "food security," "innovation," and "ICT". According to the Food and Agriculture Organization (FAO), food security is achieved "when all people, at all times, have physical, social, and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life." This conceptualization emphasizes two critical elements: (1) food availability and access; and (2) food quality and safety.

Table 6. Most frequently used keywords based on keyword co-occurrence clustering.

Cluster	Theme	Most Frequent Keywords
1	ICT for agriculture and food security	Agriculture; food security; value-chain; innovation; coronavirus; ICT; LR (Logistic Regression); climate change; SDGs (Sustainable Development Goals); technology; food system; technology adoption; precision agriculture
2	Food waste and circular economy	Sustainability; SC; food waste; LCA; logistics; circular economy; food; biomass; biofuel; bioeconomy; bioenergy; biofinery; environment; food loss
3	IoT and blockchain in FSCs	FSC; IoT; blockchain; SCM; food safety; traceability; big data; RFID (Radio Frequency Identification); Industry 4.0; ML (Machine Learning); AI (Artificial Intelligence); simulation; transparency; WSN (Wireless Sensor Networks); cold chain; integration
4	GIS and consumer perceptions	GIS; diet; obesity; adolescent; children; risk factor; social media; fast-food; nutrition; stakeholder; food insecurity; perception; vegetable; built environment; physical activity
5	Indian and Chinese AFSCs	AFSC (Agri-food Supply Chain); India; agribusiness; China; case study; SME (Small and Medium Enterprises); consumer; decision making; biotechnology; IT (Information Technology); risk; Brazil; agricultural product; e-commerce; entrepreneurship

As a complex and multidimensional concept, food security is an issue that needs to be urgently addressed due to the exponential rise in the world population, which is estimated to reach 9.6 billion in 2050 [98]. In this context, Ref. [99] argued that "value-chain agriculture" constitutes a potential solution to incorporate smallholding farmers into commercial relationships to overcome food shortages. The objective of value-chain agriculture is to increase market connection and agriculture productivity as well as maximize the ecological and economic value-generating potential of farmers. Moreover, policy objectives such as food security and sustainable development goals (SDGs) can be realized by the promotion of innovation and the adoption of new information communication technologies (ICT) [86]. The author of [100] notes a need to reorientate food innovation systems towards sustainability and equality by maximizing crop yields and inputs quality. Similarly, Ref. [101] posit that an innovation-based approach among food industry stakeholders can improve food security, simplify access to markets, fight poverty and malnutrition, and boost sustainable natural resource management.

While technological innovations are imperative, FSCs still encounter food insecurity and climate change. Agriculture is an important sector in greenhouse gas (GHG) emissions and continually struggles to mitigate climate change by limiting GHG emissions [102]. Excessive consumption of resources (e.g., land, water, energy, pesticides, fertilizers, etc.) can degrade the environment, accelerate deforestation, and worsen climate change [103]. In addition, exposure to high temperatures can stress the physiological, morphological, and metabolic processes of agriculture crops and deteriorate the quality attributes of food products [104]. However, the continuous instrumentalization of agri-food activities provides farmers with a wealth of novel data-driven services [83] and propels smart farming or precision agriculture [86]. This decisive phenomenon enables the improvement of farming processes in terms of efficiency, automation, and environmental concerns [105]. Integrating multiple ICTs, precision agriculture fosters agri-food sustainability transition by optimizing resource productivity, overcoming inefficiencies, reducing management costs, and streamlining food chain coordination [106].

While the literature on the possibilities of ICTs in agriculture and food security is abundant, there is still a need to comprehend how sustainability goals can be embedded into the development of technology-enabled agricultural processes and products [107]. The investigation of the ways to maintain food security and balance economic, environmental, and social sustainability by adopting new technologies is another promising avenue for future research as all policymakers and government bodies across the globe are placing food

security on the top of their political agenda [108]. As an alarming threat to the agriculture industry, climate change perceptions among FSC stakeholders should be examined in order to motivate practices and technologies that lower agriculture's side effects and mitigate climate change. Finally, scholars should draw upon the domain's wealth of current knowledge to clarify how precision agriculture can not only offer noticeable benefits to farmers but also concurrently improve resource management and conservation to meet sustainability requirements.

4.1.2. Food Waste and Circular Economy

Food systems depend heavily on natural resources such as land, soil, and water. An enormous amount of inputs such as pesticides, fertilizers, energy, and human labor are employed in production, processing, transportation, distribution, and storage processes to deliver food products for human consumption. As a result, food waste represents a waste of land, water, inputs, non-value-adding activities, and unnecessary factors contributing to climate change [91]. Keywords such as "sustainability," "food waste," "LCA" (lifecycle assessment), and "circular economy" are therefore included in this cluster. From the environmental and food security perspective, food waste is a key aspect for sustainable development, which requires implementing different food reduction measures to achieve sustainability [98,109,110].

According to [110], LCA can be used to model food waste because it is an appropriate tool to assess technological and managerial solutions to dysfunctional FSCs. LCA provides information to consumers and other primary stakeholders in the food industry on the environmental impact of food products, thus increasing food chain transparency and traceability [111]. In a circular economy, LCA also can environmentally assess food products or circular FSC business models by offering improved ideas to circular FSC solutions [112]. For example, the evaluation of waste management, including logistics, can be facilitated with LCA implementation in a circular economy by reducing fertilizer consumption, improving waster-efficiency measures, and optimizing management along the whole FSC to limit food waste and losses during production and distribution [110]. In the frame of circular economy, Ref. [113] contended that agri-food products would have significant potential as the circular economy approach enables farmers to reduce environmental and economic costs caused by food waste disposal. The joint application of circular economy and bioeconomy in the food industry is expected to provide eco-efficient production of renewable food and energy efficiency, thereby responding to the basic needs of consumers [114]. The conversion of produced biomass such as crops and organic waste materials into bio-based products such as biofuels and bioenergy could balance and limit fossil energy use and satisfy primary energy demands [115].

From the discussion of this cluster, it appears that there is still ample room for investigating how the circular economy is taking form and operating in today's food systems to achieve sustainable development [116]. To date, for example, few studies exist to demonstrate a practical approach to implement the circular economy and bioeconomy concepts in the FSC. The lack of practical use cases undermines the ability of food organizations to devise appropriate strategies and policies in favor of circular FSC business models. A contribution opportunity from future research would be to clarify how LCA can support the decision-making processes of food organizations throughout the different stages of a circular bioeconomy model. In spite of the increasing interest in circularity practices, there is a paucity of research that showcases new strategies aimed at reusing or recycling food materials through innovative technologies and solutions. Therefore, the examination of the contextual factors that determine the adoption of emerging technologies in reducing food waste and transitioning toward the circular economy is required. As such, the comprehension of the organizational objectives, activities, and environment can help practitioners identify the adequate business context in which circular economy principles can be implemented in the FSC. Further discussion is also required to understand how

circular FSCs outperform linear FSCs not only in terms of environmental performance but also in terms of economic and social sustainability.

4.1.3. IoT and Blockchain in FSCs

The blue cluster revolves around the role of IoT and blockchain in increasing FSC efficiency, transparency, and traceability. Because of the more highlighted role of IoT and blockchain in the extant literature compared to other technologies, we labeled the cluster as IoT and blockchain in FSCs. It is also evident from most relevant keywords including "FSC", "IoT", "blockchain", "SCM", "food safety", "traceability", "transparency", and various technologies investigated by scholars to revolutionize the FSC. Traditional FSCs have faced multiple food safety and security issues due to incomplete and asymmetric information, thus requiring innovative solutions to enhance FSC traceability and transparency [12,117–119]. The issue becomes evident considering the cold chain and COVID-19 pandemic [13]. IoT is considered a paradigm shift in supply chain management [21,47] and FSC specifically [7,120]. Its enabling role in integrating cyber and physical worlds and various technologies such as WSN, RFID, big data, and AI techniques (e.g., machine learning) equipped the FSC with high business intelligence to improve decision making, achieve economic and sustainable goals, and provide food safety and FSC transparency [7].

To be more specific, in the first phase, a huge amount of data (e.g., humidity, temperature, soil moisture, etc.) is extracted by sensor nodes from the field. The data is then transferred to the base station after minor processing. More in-depth processing is done by conducting big data analytic methods and AI techniques to provide helpful information for site-specific management and precision farming [3,7,8]. Additionally, IoT could simplify the upstream and downstream parties' collaboration. All the companies across the supply chain could benefit from the integrated near real-time data and analytics that IoT devices provide [13]. In the next phase of the supply chain, IoT devices measure, analyze, and store various data from raw materials purchasing, production, transportation, shipping, and warehousing conditions, among other parts of the food logistics. For example, various conditions such as temperature, time, humidity, product life cycle, and location history in different stages could be extracted by various sensors (e.g., geospatial technologies, RFID, near-field communication (NFC), temperature sensors, and humidity sensors) and analyzed by computing technologies, big data, AI, etc. [17,53,121]. The task of data and information assignment to the products and also the task of reading or accessing the information could be automated by RFID tags [13]. Due to the abovementioned benefits, the interests of various stakeholders, including supply chain members, the public, and institutions regarding food safety, security, quality, traceability, and transparency, could be served simultaneously.

However, central systems and databases may not be suitable for handling FSC data for several reasons [122]. The decentralized nature of IoT encompassing an enormous number of distributed devices indicates the need for scalable decentralized systems [123]. Moreover, centralized systems are more exposed to hacking risks and abuse of power [123,124]. Also, consumers usually fail to acquire all needed information and trace the product from its origin [51]. Hence the reliability and information accuracy issues arise [125]. Additionally, a single point of failure may lead to system disruptions [126]. As an emerging technology, blockchain has the potential to solve accessibility, security, accountability, and accuracy problems [122]; blockchain technology offers digital trust, which could be substituted with real-world trust among unreliable parties (e.g., supply chain members) [126,127]. It could contribute significantly to the IoT-based supply chain. Blockchain could establish trust as the data usually is stored in time-stamped, tamper-proof, immutable, and chronologically-connected blocks secured with cryptography and distributed in several nodes [17,51]. Because the data is distributed and there is no central authority or trusted third party, the data is completely transparent and secure, and the stakeholders could rely on the data provided and trace the product from the very beginning [127–130].

Although they offer huge potentials, IoT and blockchain integration faces several challenges. Empirical research based on successful implementation and good practices is scarce [17]. The interoperability and standardization issues are another drawback in successfully adopting the technologies, which offers an exciting pathway for future researchers [51]. Also, there are limitations in achieving scalability, energy efficiency, stability, privacy, and security simultaneously for blockchain-based IoT solutions [50] as more energy-efficient and scalable consensus mechanisms and solutions usually face security challenges. Moreover, implementing such systems requires considerable investment [50]. These all indicate the need for developing a new system design or novel distributed ledger technology architecture.

Blockchain regulation is another obstacle [51] that should be addressed in future studies developing frameworks in collaboration with governments, health departments, and other related institutions. At the sensing level, the energy efficiency of IoT devices needs to be addressed. Improving sensors' energy efficiency [50], enhancing power supplies [131], and developing energy-independent sensors [132] are among interesting topics. Furthermore, the connectivity of IoT devices has great potential for upcoming projects. The promising solutions include adopting fog computing, edge computing, and blockchain [122]. As a socio-technological concept, the acceptance and implication of the technologies by supply chain parties and consumers are of great importance and urgently need related research [122].

4.1.4. GIS and Consumer Perceptions

The fourth cluster investigates the technology-enabled FSC from the perspective of consumer behavior and health care. This focus tries to explain the measures for understanding the local environment and the influence of the built environment on health and eating habits. The following keywords strengthen the argument: "GIS"; "diet"; "obesity"; "fast-food"; "nutrition"; "perception"; "vegetable"; "built environment"; and "physical activity". The importance of diet is undeniable in having a healthy life, and obesity-related diseases such as heart disease, diabetes, and cancer are among important causes of premature mortality and preventable deaths [133–136]. Scholars in this cluster investigated and compared the measures for determining the food environment [137–140].

Two of the most used measures include GIS technology [141,142] and perception based on surveys, interviews, etc. [143,144]. The first (GIS technology) has been considered a promising facilitator of studies related to dynamics between health mapping, environmental exposure, and health care changes [134]. The second, or the perception of distance to various food outlets, is a complex phenomenon dependent on different variables such as physical fitness [145,146], the level of socialization and connection with neighbors [147], and the motivation to, for example, buy from a specific neighborhood [148]. On the other hand, the researchers in this cluster examined how the local built environment and food insecurity affect healthy diet and physical activity [149–152]. In other words, the availability of fruits and vegetables, supermarkets, groceries, and fast-foods relation to diet and obesity has been explored. Among others, Refs. [143,153–155] reported a positive relationship between the availability of healthy food or positive built environment perception and healthier diet and physical activity.

Considering the empowering role of GIS technology in the built environment and health care studies, researchers need to conduct their studies to expand and enhance GIS applications in the domain and develop GIS data analysis techniques such as the spatial regression method [134,156]. Furthermore, other geospatial technologies could provide promising solutions for the domain. Combining GIS, Global Positioning System (GPS), and Remote Sensing (RS), also known as 3s, could revolutionize the obesity-related research, for example, by measuring the exposure based on GIS and wearable GPS devices, or by including the time of daylight, temperature, and rainfall based on RS technology [156].

Although arduous endeavors have been made to explore objective and subjective neighborhood impacts on a healthier diet, more efforts should be made to understand

their inter-relationship and what factors modify their relation (e.g., residents' engagement in the local environment) [147]. Also, an under-investigated domain is how to successfully develop health promotion strategies and implement public health interventions to improve the perception of the surrounding environment based on the findings of academic researches [157,158]. Moreover, various studies reported other elements that affect healthier diet and food intake such as budget, self-rated health, quality, preferences, acceptance, cultural tailoring, accommodation, and carrying difficulties [156,159–165], and indicated that the real consumption of fast foods might differ to exposure rate [152]. These all indicate the need for developing new researches based on different perspectives and contexts to explore what affects a healthier diet. Additionally, as physical activity and healthy food environments are closely related to human physical and mental health, another under-researched pathway for future studies could be exploring both simultaneously instead of considering them isolated [166].

4.1.5. Indian and Chinese FSCs

The last cluster revolves around the Indian and Chinese FSC. Both China and India are among the largest producers and exporters of agricultural products, and many lives in both are dependent on agriculture and the food industry due to employment, farming, etc. [167–169]. Also, both have been considered highly emerging economics and markets [170–172]. As with other emerging economies, the governance and population issues are relevant [173]. However, the agriculture sector and FSC in these countries is still traditional due to significant inefficiencies and food wastage [168,169,174], food safety concerns, food security risks, and trust issues [175,176],

Scholars in the current cluster have addressed the problems exploring and examining various areas in the domain, including supply chain integration and collaboration [167,168,176], the effects of macro (e.g., environment and governance structure) and micro (e.g., interpersonal relationships) variables on supply chain information sharing [173]. Oher topics include sustainable growth of small and medium enterprises (SME) and entrepreneurship as the engines of economic development [169,173,177], biotechnology and its enormous potentials for entrepreneurs and agriculture improvement (e.g., grain productivity) [178,179], and the incorporation of cutting-edge technologies such as IoT, blockchain, AI, RFID, etc., to alleviate inefficiencies, improve transparency and traceability, and improve decision making [21,177,180–184]. Technology acceptance by consumers and e-governance [185], sustainability and green practices [186,187], and FSCs during the epidemic crisis, specifically COVID-19 [188], also attract significant attention.

From this paradigm perspective, researchers have identified under-studied research gaps that lead to interesting future topics. The shortcomings in supply chain management in India and China, as well as many other countries, may be caused by the lack of successful implications of academic research. Future collaboration between researchers and practitioners is needed to address this stage by conducting empirical problem-oriented researches (i.e., identifying the barriers from an empirical perspective) [168]. Additionally, future researchers could compare developed and developing economies and investigate the best practices to be implemented in another context. This could be done, for example, by exploring the institutional context of the countries [173]. Sustainability in the agri-food sector is an understudied subject in developing countries [187]. This could be considered a fruitful future research avenue based on future national and global plans to achieve zero carbon emissions. Furthermore, food safety and security after the COVID-19 pandemic and increased consumer awareness guide the food industry toward safer no-touch initiatives, which is also a worthy future topic [188].

4.2. Key-Route Main Path Analysis

In order to obtain a broader and more complete view, we further carried out a key-route main path analysis. In general, key-route main paths constitute several main paths generated based on key-routes, which represent the top significant links in a citation

network. While the main path contains multiple sequences of citations from a set of beginning points to another set of ending points [189], a key-route main path corresponds to a single sequence of citations. Unlike multiple main paths [190], key-route main paths ensure that the top significant citations are involved in its sequences of citation links. Including the top significant citation links in the multiple sequences indicates the governing structure of knowledge diffusion trajectories and enables the pattern of convergence and divergence to surface, in case it exists. Figure 5 depicts the routes produced from the top 26 links in research related to technology-enabled FSCs. The arrow in the figure depicts the course of knowledge flow, and the arrow thickness represents the size of a traversal weight, which is the proportion of the number of times a specific citation appears among all the different paths between a source and sink to the total number of paths between them [191]. The thicker the arrow is, the higher the impact of the link's knowledge diffusion [192].

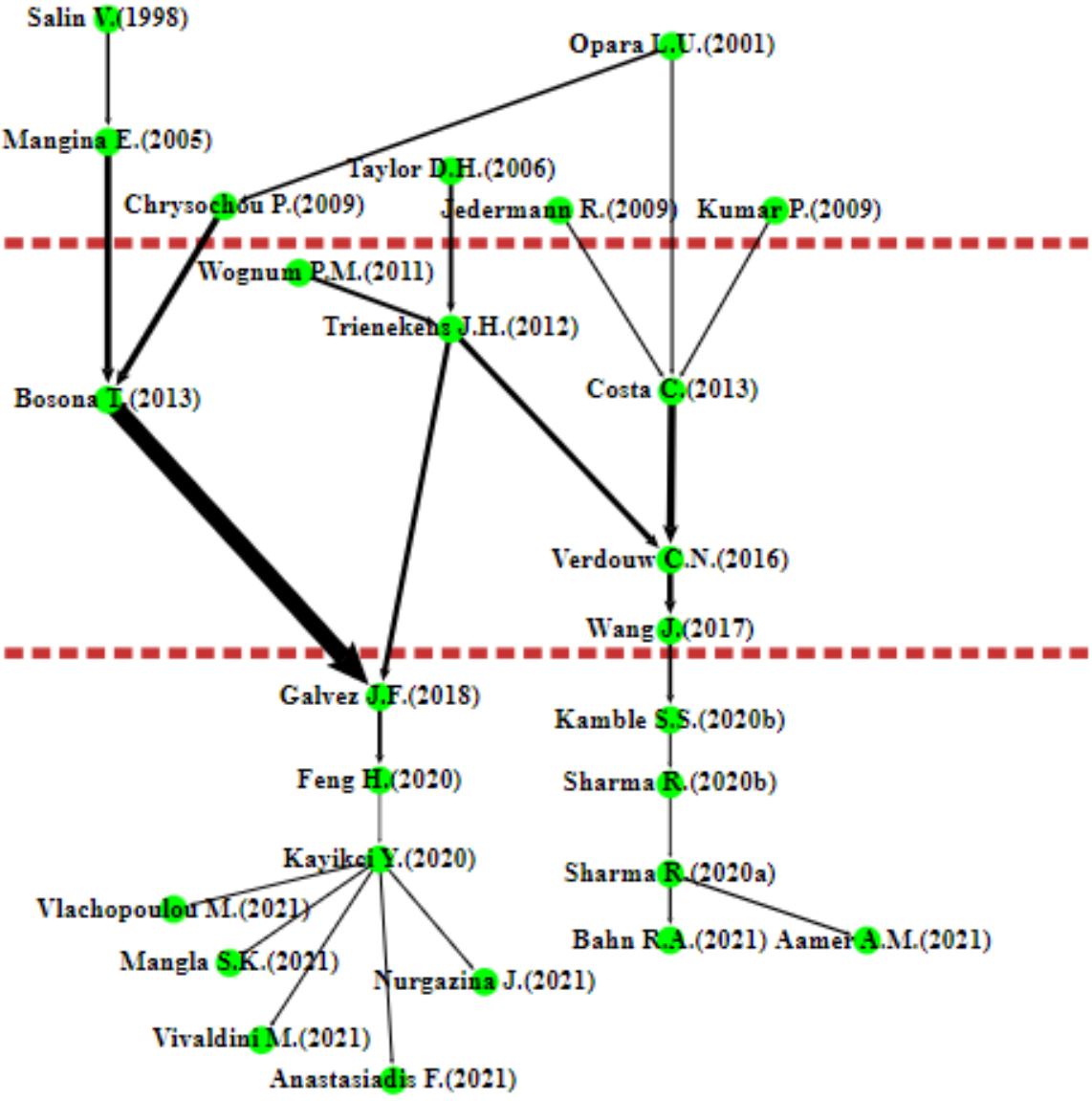


Figure 5. Key-route main path (based on the top 26 links).

We observe that the key-route main paths reveal comprehensive knowledge diffusions in this research field. With the convergence and divergence of paths in the network, the key-route main path tells a wonderful story in the formation of technology-enabled FSC research.

Between 1998 and 2009, the researchers mainly focused on investigating information technology and RFID applications for food traceability. For example, Ref. [193], being the first paper on the key-route main path, marks the initial development of technology-enabled FSC research. In this study, the author explored the distinctions between supply chains for functional vs. innovative products and argued that effective IT systems in the agri-food industry could create information that will offer competitive advantages to the whole food chain, to the degree that information is shared. Later, in response to public concern for food safety, sustainability, animal welfare, Ref. [194] presented a worldwide overview of traceability metrics in food trade and explored some of the factors in developing and developed nations. To integrate traceability into current food safety standards and trade agreements, there is a need to invest in IT for data collection, storage, and management. Moreover, Ref. [195] provided a model of smart FSC that optimizes efficiency within the supply chain. Ref. [196] further noted that consistencies with information systems and data handling processes are essential to maintain alignment of demand and supply in the agri-food industry. In 2009, three papers emerged to study the potential of RFID for food traceability systems. The authors of [197] provided fundamental terminologies and concepts related to RFID technology and its use in the agri-food sector. Several applications of RFID are highlighted, including supply chain management, temperature monitoring of food products, and food safety; meanwhile, the challenges of deploying the technology are limited read range, read precision, non-interoperable standards, cost, privacy and security concerns, and recycling difficulties. Another study, Ref. [198], investigated how miniaturized RFID temperature loggers can be customized to assess the number of local deviations, capture temperature gradients, and determine the lowest number of sensors required for reliable monitoring within a container or truck during perishable food transportation. Finally, Ref. [199] explored the factors that impact consumers' perceptions of traceability information carriers and found that the level of confidence in the information provided, perceived levels of convenience, influence on food quality and safety, influence on consumers' health and the environment, ethics, and privacy are among the key factors affecting consumers' perception of these technologies.

From 2010 to 2017, scholars have started to focus on the development of systems aiming at increasing sustainability and transparency in FSCs. For example, Ref. [111] analyzed the present situation of information systems to promote sustainability in FSCs and communications towards important stakeholders. It was found that information provision mostly concerns the single isolated business partner; therefore, technology use should be intensified to increase transparency, supply chain collaboration, and stimulate innovation and competitiveness. Based on [111,200] investigated the specific issues of FSCs (e.g., information integrity, timeliness, and actuality) and argued that information sharing backed by information systems and IT is required to be able to respond to the wide variety of information needed by diverse chain actors, consumers, and the government.

In [201], a comprehensive literature review of food traceability challenges was conducted, and several technologies for traceability were identified, including external tags, chemical marking, physical marking, DNA markers, GIS, GPS, and EDI. Another review was also made by [202], who examined the current advancements in RFID in the food sector and concluded that this technology improves traceability of food products, monitors the condition of their processing conditions throughout the FSC stages, increases process efficiency, and provides consumers, government agencies, and customs officers with accurate information for real-time tracking of foods. The next paper on the path was authored by [203], who investigated the notion of virtualization in the FSC from the IoT perspective and provided an architecture to develop supporting information systems. The adoption of IoT makes the FSC a self-adaptive system in which smart products function, make decisions, and learn autonomously. Finally, Ref. [204] suggested a food pre-warning system based on association rule mining and IoT to promptly monitor all sensory data of the entire FSC and automatically pre-warn. The proposed system aimed to enable managers in food

manufacturing companies to detect food safety risks early, support decision-making, and guarantee food safety and quality.

From 2018 to 2021, two different branches are plainly formed. The left branch comprises eight primary studies discussing the potentials and challenges of adopting blockchain technology in the FSC to ensure food quality and safety. For example, Ref. [17] reviewed the possibilities of blockchain technology for ensuring authenticity and traceability in the FSC. Blockchain is a valuable means of tracking traceability difficulties and assuring FSC visibility and transparency by chronologically securing data records from chemical analyses so they are hard to modify later. The next two papers, [15] and [51], investigated the role of blockchain to improve food traceability from different perspectives such as people, process, and performance. After [15], several sub-branches appeared; [50,205,206] examined the applications, challenges, and societal impacts of blockchain technology in the FSC, while [207] examined the level of customer centricity in FSCs in the context of a traceability system and demonstrated that health, trust, quality, nutrition, and safety-related values are critical determinants for consumer acceptance of a traceability system. Finally, Ref. [208] explored several forms of "agri-food tech" digital models and assessed their function in the agri-food industry.

The right branch contains five papers that dealt with the performance of digitalized FSCs and the role of new technologies to mitigate supply chains risks and the COVID-19 pandemic. The first of these, Ref. [84], reviewed 84 academic papers from 2000 to 2017 to realize the level of analytics employed (descriptive, predictive, and prescriptive), the objectives of the sustainable agriculture supply chain, and the supply chain processes from where the data gathered, and the resources allocated for agriculture activities. Data analytics can manage the never-ending complicated difficulties in FSC systems and achieve food safety, food security, and environmental sustainability. In the next paper, Ref. [36] made a thorough overview of machine learning applications in the agri-food industry. According to the authors, these technological solutions maximize the overall efficiency of the FSC and solve the various difficulties encountered by farmers, including crop yield, soil condition, and disease control. Similarly, Ref. [209] argued that deployment of industry 4.0 technologies could be among the strategies necessary to mitigate the challenges brought by the COVID-19 pandemic, such as supply and demand risks, financial risks, logistical and infrastructural risks, and operational issues, etc. Finally, the last two papers, Refs. [210,211], examined the potential and challenges of digitalization and IoT adoption in the FSC. Therefore, recent papers at the end of the key-route main path revealed several emerging technologies that contribute to the development of sustainable FSCs, such as blockchain, data analytics, and machine learning.

5. Conclusions, Research Implications, and Limitations

5.1. Conclusions

The main purpose of this study was to summarize the literature surrounding technology-enabled FSCs and expand the current literature by noting numerous knowledge gaps for future research. Building on bibliometric techniques and content analysis of selected papers, we identified the most relevant themes in extant research and uncovered emergent and promising routes for future studies. To undertake the analysis, a collection of 2140 publications was selected and considered for the final review. The review results can be relevant to researchers actively investigating digitalization in the FSC. Despite the rising literature on technology-enabled FSCs, there is still a paucity of publications offering a comprehensive picture of the future advances of digitalization in the food industry, extending the understanding of the topic and filling the knowledge gap. As a result, our analysis aims to fulfill this objective by identifying numerous themes and research areas at the intersection of digitalization, FSCs, and sustainability. Several significant insights can be derived from this study.

First, the number of papers related to digital FSCs has substantially grown over 1975–2021 (until June). The journal-wise distribution of selected papers suggested that *Jour-*

nal of Cleaner Production, *Sustainability*, and *PLoS ONE* are the leading venues contributing to the literature pertaining to technology-enabled FSCs. Our analysis demonstrated these journals and their role in advancing digitalization in the food sector over the years. Concerning the global impact, North American and European countries are the most prolific. The present research offers some fascinating insights about the role of digital technologies to assist FSC operations and boost the efficiency and sustainability of food processes. In terms of productivity, Hobbs J.E. and Mangla S.K. are the most prolific authors. In terms of institutional contributions, Wageningen University and Research is the most productive institution. The keywords analysis indicates that the sustainable development of FSCs rests on the integration of modern technologies such as IoT, blockchain, GIS in agri-food firms [141,206,211]. The embrace of digitalization allows real-time monitoring and control of FSC operations, ensuring food safety and quality and increasing consumer satisfaction [210]. By means of digitalization, FSC partners can increase the efficiency of their operations and create new possibilities of interactions with consumers directly [212–214]. Moreover, the integration of new technologies can generate new professions or businesses associated with digitalization. From the perspective of environmental sustainability, the influence of new technologies is significant due to their ability to lower resources (e.g., water, fertilizers, waste) use, support the transition toward the circular economy, and mitigate climate change. Lastly, the analysis of the core content and the historical development of FSCs reveals five major research clusters and three critical periods for digitalization in the context of FSCs.

We highlighted future research directions for each cluster. Regarding the first three clusters, future research avenues primarily include how to successfully embed sustainability and circular economy principles into technology-enabled FSC practices [92,106]. This encompasses various stages, from agricultural input to food production and distribution processes. It is specifically essential to address implementation challenges based on more technical and empirical research. Several improvements for integrating cutting-edge technologies and making them energy-efficient, affordable, and cost-effective are needed [131]. Furthermore, there is a need to transform traditional supply chain architecture, business logic, and business models toward more non-linear sustainable systems. Novel technologies regulation is another exciting and under-researched subject in these foci. Considering the fourth cluster, there is a call for adopting more holistic approaches to investigate or summarize how and to what extent various elements could affect healthier diet and physical activity. Geo-spatial and remote sensing technologies [134,140] could complement such investigations. Innovative research designs which incorporate these technologies or develop them at the technical level are needed. The fifth cluster indicates the need for more collaboration between industry and academia as well as between developed and developing countries for initiating sustainable solutions to achieve sustainability and food safety and security goals [20,174,176].

5.2. Research Implications

For scholars seeking to obtain an increased understanding of digitalization in the FSC, the main content of the pertinent literature was discovered using keyword frequency analysis. The main findings derived from the keyword co-occurrence network analysis are the in-depth examination of the role of ICT in supporting agriculture, ensuring food security, and achieving sustainable development goals. More recently, though, scholars have focused their attention on emerging technologies such as IoT, blockchain, and AI. The digitalization of the FSC is predicted to add more value for agri-food firms and enhance their operations, such as cultivation, food processing, transportation, and traceability. To obtain a better knowledge of research at the intersection of digitalization and the FSC, researchers may refer to the articles analyzed in this review to understand how the ongoing improvement in digitalization and the use of modern technologies has allowed the automation of supply chain processes from upstream to downstream and the increase of operational efficiencies. Furthermore, technological advances in FSCs such as IoT contribute to the development

of data-rich systems in the food sector by increasing access to information related to crop yield, weather, and diseases.

Being mindful of the most prolific authors in the literature will enable potential researchers to forge new research collaborations, initiate further projects, and improve the overall quality of future academic endeavors. In addition, the keyword co-occurrence network analysis serves to expose the structure of themes and topics discussed in the area of digitalization and the FSC. Likewise, it makes it easier to discover the core content of digitalization research and reveals several knowledge gaps. The literature is mainly focused on three main themes: (1) ICT for agriculture and food security; (2) food waste and circular economy; and (3) IoT and blockchain applications in FSCs. Given the shifting global dynamics, conventional approaches of guaranteeing food security and safety will not be sufficient and sustainable alone. Therefore, it is essential to develop innovative food security systems that reduce food waste throughout the different stages of the FSC, including production, transportation, and distribution.

In the current digital era, the rising disruptive technologies such as IoT, blockchain, and AI are progressively affecting the modus operandi of the food industry, giving birth to data-driven, sustainable, and circular FSCs. The results from the keyword co-occurrence network also highlight the role of geographic information systems (GIS) to increase food exposure and the focus of research on FSCs in developing countries, including India and China. Overall, the favorable influence of digitalization may be realized if technologies are combined effectively and rationally. However, the advantages of digitalization do not come without technical, organizational, regulatory, and ethical issues. In this regard, scholars and practitioners should closely work together to enhance the technical aspects of technologies, strategize the effective guidelines for implementing each technology, and carefully plan their investments in smart and data-driven FSCs. To uncover the studies that play critical knowledge diffusion roles in technology-enabled FSCs, we conducted a key-route main path analysis. The path systematically exhibits three research development cycles, including the earlier focus on RFID applications for food traceability, the development of systems for sustainable and transparent FSC, and the potentials of cutting-edge technologies such as blockchain, big data analytics, and machine learning in the FSC.

In conclusion, the present work adopts an objective, rigorous, and useful approach to synthesize related research themes and identify various avenues for further research. To the authors' best knowledge, this is the first effort to study the intellectual structure of technology-enabled FSCs and their role in developing a sustainable food sector based on a comprehensive set of journal articles published over nearly five decades. Our results will be beneficial for researchers and practitioners to gain an increased understanding of the current status of research at the intersection of digitalization and the FSC, and our suggestions for future works will enlighten them on the research gaps that require further attention.

5.3. Limitations

The analysis of research related to technology-enabled FSCs offers many new insights and considerably contributes to the literature, documenting the development of academic output, leading journals, authors, academic institutions, and contributing countries. However, no bibliometric study can offer a complete picture of a field of study. While the sample of selected articles is comprehensive, it is not exhaustive, and the dataset might be biased due to the filtering criteria. As is commonly done in review-based studies, our focus was on scholarly and English-speaking journal publications, eliminating potentially intriguing and important research being produced in other sources (e.g., books, conference proceedings) or languages. In addition, a significant number of studies from the selected sample are not cited here, which is endemic to all bibliometric analyses [60,215–217]. Nevertheless, as per our common knowledge of the topic, we are confident that the publications retrieved from the Scopus database provided us with a comprehensive collection of the most important research that scholars have produced to date in regard to digitalization and the FSC. Even

though the key-route main path explored is illustrative of the knowledge dissemination routes for the development of digitalization in agriculture, citation bias is inevitable in citation network analyses, given that studies with positive results are more likely to be referenced than those with negative results [218]. Moreover, it is vital to emphasize that our review includes academic results, and the classification by region or affiliation area does not enable us to make conclusions on the existing state of technology-enabled FSCs or their development in a certain nation.

Building on the findings of this analysis, future research should broaden the context of this review and strengthen its findings by collecting additional data from other major academic databases such as the Web of Science. In addition, future bibliometric studies may include other important knowledge sources such as books, chapters, and conference papers to obtain new insights. Grouping research topics based on co-citation network or bibliographic coupling may be another interesting method in future bibliometric research.

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