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Smart agri-food supply chains during the 2020s: Mapping emerging trends, prevailing themes, and future directions

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A R T I C L E I N F O

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A B S T R A C T

In recent years, the integration of digital technologies to optimize Agri-Food Supply Chain (A-FSC) management has received significant attention. This study aimed to comprehensively review the literature surrounding Smart Agri-Food Supply Chains (SA-FSCs) and explore the prevailing themes, emerging trends, and foundational and influential themes. A bibliometric analysis utilizing keyword co-occurrence (co-word) and co-citation networking was employed to analyze the data. The documents extracted from the Scopus database were screened through the PRISMA protocol, and 3334 articles published between 2020–2024 were included in the analysis. Bibliometric analysis identified the most influential authors, countries, journals, references, and annual growth trends, as well as international participation, and revealed an evolving positive trend in SA-FSCs during the current decade. Co-word analysis revealed that emerging trends in SA-FSCs can be summarized around five axes: "food safety and food waste," "A-FSC management and traceability," "Sustainable development in A-FSCs," "Digital technologies in A-FSCs," and "Innovation and technology adoption in A-FSCs". Co-citation analysis, supplemented by a detailed content analysis of key articles, clustered foundational and influential SA-FSC themes into four axes and highlighted the central role of traceability, particularly blockchain technology, among other digital technologies of SA-FSCs. Finally, based on the findings of this study regarding prevailing themes and foundational and influential themes, a structured and concise research agenda was formulated to guide and enhance future studies on SA-FSCs. These findings provide critical insights for researchers and policymakers to identify and target the most pressing needs within the SA-FSC domain.

1. Introduction

Agri-food systems have historically been vulnerable to shocks from natural disasters, conflicts, and price volatility. However, the COVID-19 pandemic in the current decade exposed their fragility to an unprecedented global disruption that compromised food security, nutrition, and livelihoods of billions over an extended period [1]. This crisis underscored the urgent need to enhance the resilience and sustainability of these vital systems [2] that produce approximately 11 billion tons of food and a multitude of non-food products annually, with an estimated gross agricultural output value of $3.5 trillion [1]. Currently, the optimal management of this volume of production and value creation in addition to sustainable inputs requires the use of digital technologies as a key priority [3]. Digitalization offers opportunities to strengthen Agri-Food Supply Chain (A-FSC) resilience, security, and sustainability amid volatile conditions [4,5]. Integrating technologies like Artificial Intelligence (AI), blockchain, cloud computing, and Internet of Things (IoT) improves information sharing, optimizes utilization, mitigates asymmetries, and fosters coordination among participants [4,6].

Transitioning to circular from linear supply chain models is crucial for economic and environmental goals, but redesigning processes poses multidimensional challenges for companies and governments [7]. Digital technologies like IoT, sensors, and big data analytics are pivotal enablers of circular economy models in agri-food systems. By sharing real-time data across supply chains, monitoring material flows, automating practices, and enhancing decision-making via support systems,

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these tools optimize resource use, reduce waste, and enable closed-loop processes where end-of-life products become secondary raw materials. However, circular economy adoption requires collaboration among stakeholders and high-quality data to design context specific models [8]. Beyond circularity, regenerative supply chains offer a paradigm shift by harmonizing production with social-ecological systems through proportionality, reciprocity, and poly-rhythmicity. Proportionality balances human activities with ecological thresholds, ensuring production scales align with local biodiversity. Reciprocity fosters mutual benefits across stakeholders and ecosystems, prioritizing eco-effectiveness, where waste streams nourish other processes. Poly-rhythmicity acknowledges interdependent natural rhythms (e.g., fire cycles, species regeneration) that sustain life, urging synchronization of supply chain operations with these dynamics to avoid systemic deterioration [9]. Digital supply chains integrating data-driven, knowledge-based, and decision technologies can drive this evolution [6]. Technologies like IoT and Cyber-Physical Systems connect the cyber and physical worlds and can be helpful in this pathway [10]. Traceability systems are pivotal for monitoring the linear to circular transition and uncovering complexities in the food ecosystem [11,12]. Identifying and tracking every unit from "farm to fork" minimizes uncertainty, prevents safety crises with public health and economic impacts, and facilitates the sustainability journey [11]. The global population reaching 11.2 billion by 2100, coupled with intensive cultivation, generates substantial waste releasing hazardous substances into ecosystems and 21–37 % of greenhouse gas emissions [13]. Furthermore, around 931 million tonnes of food waste were generated in 2019, with 61 % from households, 26 % from food service, and 13 % from retail, suggesting 17 % of total global food production may be wasted; which further emphasizes this issue [14]. A significant challenge in contemporary Agri-Food Supply Chains (A-FSCs) lies in balancing rising demand with the reduction of pollution and waste from agricultural operations [15]. Enhancing architectures for monitoring material flows, effectively managing resource capture, and facilitating information communication can be instrumental in addressing these obstacles [11].

A-FSCs comprise a complex network across production, processing, distribution, and consumption stages that add value except consumption itself [16]. The call for sustainable A-FSCs intensified over the last decade amid growing cognizance of environmental and social impacts [2,16]. Transparency and traceability (T&T) are critical enablers for achieving the United Nations Sustainable Development Goals (SDGs) like zero hunger, food security, decent work, and environmental sustainability. However, widespread T&T adoption is hindered by unaddressed technological and collaboration challenges. Robust solutions like blockchain are needed to drive transparency, trust, and sustainability in traditional error-prone paper-based systems in A-FSCs [17]. The fragmentation of geographically dispersed stakeholders has hindered the development of integrated traceability architectures for multi-dimensional monitoring. Additionally, the lack of data standards discourages sharing, negatively affecting transparency and the ability to conduct quantitative assessments [12]. Furthermore, the paradox of food overabundance amid inequitable access highlights the significant role these systems play in contributing to the climate crisis [3]. Experts and policymakers catalyzed transformation calls to ensure sustainability and nutritious diets. Smart agriculture and the fourth industrial revolution (Industry 4.0) are pivotal for cleaner, greener, and more efficient production via optimal data-driven decisions [3]. However, digital innovations decrease some costs through transparency while increasing others like data protection. Thus, strategies toward this transformation should carefully evaluate firm characteristics, objectives, and technological capacities to manage this complex transformation, coordinating and prioritizing essential dimensions of technology use, value creation changes, structural shifts, and financials in A-FSCs during the current decade [3].

Building on these technological advancements and sustainability imperatives, the concept of the smart agri-food supply chain (SA-FSC) has emerged as a comprehensive application of Supply Chain 4.0 principles. Leveraging Industry 4.0 technologies such as IoT, blockchain, AI, machine learning (ML), robotics, big data analytics, cloud computing (CC), and cyber-physical systems, the SA-FSC enables real-time monitoring, intelligent decision-making, and adaptive responses across the agri-food network [18,19]. By integrating partners through interconnected systems that support data-driven resource allocation, sustainability, and resilience, while minimizing inefficiencies such as stockouts or delays [20], this model transforms traditional, isolated operations into collaborative, technology-enabled ecosystems characterized by integration, adaptability, and self-optimization. The conceptual framework of the SA-FSC (Fig. 1) is multi-level, beginning with enabling smart technologies, progressing through intelligent operations (smart flow, smart driver, and smart decision), and culminating in fully integrated, self-optimizing networks. This architecture supports environmental, economic, and social compliance, as well as corporate social responsibility, by improving transparency, resource orchestration, and stakeholder engagement. Ultimately, the SA-FSC represents a dynamic, evolving ecosystem that aligns technological innovation with sustainable, adaptive, and collaborative value creation [19], providing a structured pathway for achieving the resilience, efficiency, and sustainability goals.

The imperative for digitalization and enhanced sustainability within global agri-food systems has spurred significant scholarly interest, evidenced by a proliferation of bibliometric analyses aiming to map this evolving research landscape. Foundational work by Latino et al. [21] quantitatively delineated the field of Agriculture 4.0, identifying core thematic clusters (technology application in agriculture, data models for prediction, smart agriculture experimentation, and decision support systems for crop monitoring), while highlighting critical gaps in research concerning performance measurement, international policy frameworks for digitalization, and product lifecycle analysis. This call for a broader perspective resonates with investigations into sustainability dimensions. Latino et al. [22] systematically reviewed sustainable A-FSCs, uncovering six primary research routes and five emerging A-FSC models (fresh, halal, local, short, perishable), yet noted a predominant focus on management issues impacting processes and systems, often overshadowing balanced exploration of all three sustainability pillars. Similarly, Şimşek et al. [23] confirmed the ascendancy of environmental sustainability research within the broader food industry, identifying key journals and clusters related to climate change, food security, and sustainable diets, but underscored a distinct paucity of studies addressing economic and social sustainability, alongside a nascent but growing interest in digitalization. The specific intersection of sustainability and agri-food supply chains was further dissected by Agnusdei and Coluccia [24], whose bibliometric and content analysis revealed four thematic clusters, with blockchain emerging as central to food security; however, they observed a persistent imbalance favoring the environmental pillar over economic and social dimensions and a critical research void concerning post-consumption phases and circular economy integration, compounded by practitioner reluctance towards technological adoption. Concurrently, the transformative potential of specific digital technologies within A-FSCs has been extensively scrutinized. Blockchain technology, in particular, has garnered substantial attention. Iryaning Handayani et al. [25] classified research into seven clusters, identifying trust and traceability as paramount benefits, while pinpointing emerging trends like resilience and halal supply chains. Chiaraluce et al. [26] specifically explored blockchain's role in high-value chains like wine and olive oil, emphasizing its capacity to combat fraud and ensure authenticity, but lamented the scarcity of studies on its environmental and social impacts and implementation costs, particularly for olive oil. Sharma et al. [27] traced blockchain's evolution from nascency towards maturity in A-FSC management, highlighting its role in enhancing transparency and trust, while Sharma et al. [28] advocated for integrating all Industry 4.0 technologies into A-FSC, identifying barriers and future research needs. Beyond

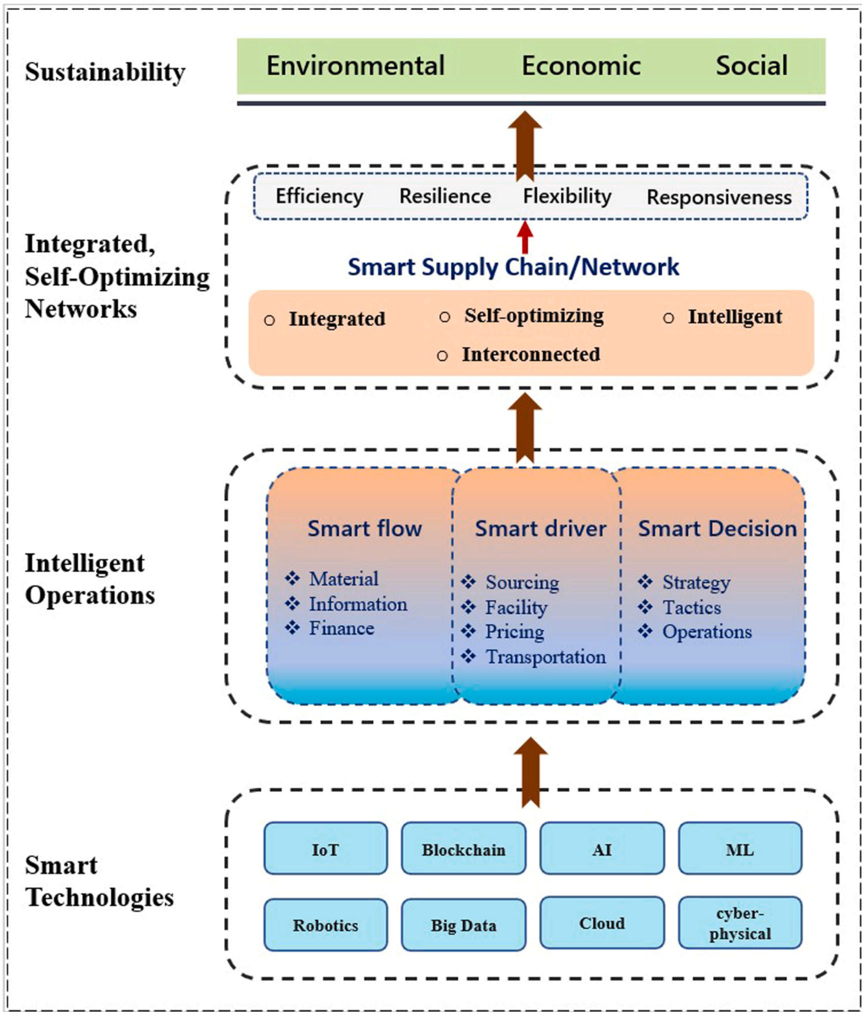

Fig. 1. Conceptual framework for SA-FSC.

blockchain, Zhang et al. [29] reviewed Phase Change Materials (PCMs) and encapsulation technologies for energy efficiency in A-FSCs, particularly within cold chains, showcasing their potential for significant energy savings and emission reduction, albeit requiring further development for multifunctionality and broader application. Lezoche et al. [30] surveyed Industry 4.0 technologies, analyzing their functional, economic, environmental, social, business, and technological impacts and challenges, framing them as essential tools for building resilient, sustainable farming systems capable of managing uncertainty through real-time data. The pursuit of sustainability has also driven exploration of alternative A-FSC models and circular economy principles. Tsoulfas et al. [31] highlighted the critical importance of Short A-FSCs for vulnerable communities (e.g., remote islands), noting their role in enhancing producer value capture and consumer trust through direct relationships, yet identified a significant research gap regarding short A-FSCs in such contexts. Chiaraluce et al. [32] performed a bibliometric analysis linking circular economy to agri-food waste valorization, finding the concept continuously evolving but dominated by European research, and called for deeper investigation into circular economy policies, regulations, and industrial symbiosis models. Synthesizing the digitalization-sustainability nexus, Amentae and Gebresenbet [33] identified blockchain, IoT, big data, and AI as key enablers for traceability, waste reduction, and resilience (especially post-COVID-19), but also cataloged significant challenges including infrastructure costs, skills gaps, regulatory uncertainty, technological limitations, and inherent A-FSC complexities, advocating for supportive policies and education. Rejeb et al. [34] conducted a large-scale bibliometric and main-path analysis, confirming the substantial scholarly interest in technology-enabled A-FSCs, identifying critical development periods, and outlining future research directions emphasizing sustainability and circular economy integration, technical improvements, novel regulations, holistic approaches to healthy diets, and enhanced collaboration. Abideen et al. [35] echoed the need for integrating multiple Industry 4.0 tools beyond IoT for resilient A-FSCs, proposing an operational framework and stressing the importance of consumer education and horizontal collaboration protocols. Sutar et al. [36] specifically focused on A-FSC resilience in the digital era, confirming COVID-19′s disruptive impact and the vital role of technologies in mitigation and recovery strategies. Finally, Trotter et al. [37] underscored the transformative potential of sustainable cold chains within global A-FSCs, particularly for Low- and Middle-Income Countries (LMICs), revealing multifaceted synergies with SDGs (poverty, food security, health, energy) but noting research gaps in capturing SDG synergies, designing multi-stage value chains, and scaling solutions in LMIC contexts, advocating for context-specific, integrated approaches. A summary of these studies is presented in Table 1, outlining their focus areas, key findings, and contributions to the digitalization and sustainability of agri-food systems.

The reviewed literature reveals extensive but fragmented research on digitalization and sustainability in agri-food systems, often limited by narrow technological focus, environmental bias, or partial methodological scope. Existing bibliometric analyses tend to emphasize specific

Table 1
Summary of key reviews on digitalization and sustainability in A-FSCs.

Study	Focus Area	Key Findings
Latino et al. [21]	Agriculture 4.0 research landscape	Identified four thematic clusters in Agriculture 4.0 and highlighted missing research on performance metrics, international policies, and product lifecycle assessment.
Latino et al. [22]	Sustainable agri-food supply chains	Mapped six research routes and five emerging A-FSC models but found overemphasis on management and limited integration of all sustainability pillars.
Şimşek et al. [23]	Sustainability in the food industry	Revealed dominant environmental sustainability research clusters on climate, food security, and diets, with minimal exploration of economic and social sustainability aspects.
Agnusdei and Coluccia [24]	Sustainability and digitalization in A-FSCs	Found blockchain central to food security but noted imbalance favoring environmental focus, lacking post-consumption, circular economy, and adoption studies.
Iryaning Handayani et al. [25]	Blockchain applications in A-FSCs	Classified research into seven clusters emphasizing trust and traceability while identifying emerging interests in resilience and halal supply chain management.
Chiaraluce et al. [26]	Blockchain in high-value food chains	Demonstrated blockchain's potential for authenticity and fraud prevention in wine and olive oil but lacking environmental, social, and cost impact assessments.
Sharma et al. [27]	Blockchain evolution in A-FSC management	Traced blockchain's maturity from emerging to established technology enhancing transparency and trust, highlighting opportunities for broader system integration.
Sharma et al. [28]	Industry 4.0 technologies in A-FSCs	Advocated integration of multiple Industry 4.0 tools for resilient, sustainable A-FSCs while identifying key barriers and necessary future research pathways.
Zhang et al. [29]	Phase Change Materials in cold chains	Reviewed PCMs and encapsulation technologies improving energy efficiency and emission reduction, emphasizing further multifunctional development and broader practical applications.
Lezoche et al. [30]	Industry 4.0 and sustainable farming	Analyzed impacts of Industry 4.0 technologies across economic, environmental, and social dimensions, identifying them as essential tools for resilient farming systems.
Tsoulfas et al. [31]	Short agri-food supply chains	Highlighted short A-FSCs' role in strengthening producer–consumer trust and local value creation, especially for remote areas, but research remains contextually limited.
Chiaraluce et al. [32]	Circular economy in agri-food waste	Found European dominance in circular economy studies on waste valorization, urging more research on policy frameworks, regulations, and industrial symbiosis models.
Amentae and Gebresenbet [33]	Digitalization–sustainability nexus in A-FSCs	Identified blockchain, IoT, AI, and big data as enablers of traceability and resilience, but noted persistent infrastructural, regulatory, and skills challenges.
Rejeb et al. [34]	Technology-enabled A-FSCs	Confirmed growing scholarly interest in digital A-FSCs, emphasizing sustainability integration, circular economy alignment, and the need for cross-sector collaboration.
Abideen et al. [35]	Industry 4.0 integration in A-FSCs	Proposed a comprehensive framework integrating multiple digital tools for resilient supply chains and highlighted the need for consumer education and collaboration.
Sutar et al. [36]	Resilience in digital A-FSCs	Showed digital technologies' key role in mitigating COVID-19 disruptions, enhancing A-FSC resilience, yet long-term digital readiness remains underexplored.
Trotter et al. [37]	Sustainable cold chains in LMICs	Revealed cold chains' significant alignment with SDGs and sustainability, stressing gaps in scaling, multi-stage design, and localized implementation strategies.

tools (e.g., blockchain) or sustainability dimensions without integrating the full spectrum of transformation within SA-FSCs. Against this backdrop, the present study addresses the need for a holistic, updated, and methodologically advanced mapping of the field. By conducting a large-scale bibliometric analysis covering the dynamic period of 2020–2024 (Fig. 4), it captures the most recent evolution of research on SA-FSCs. Its comprehensive thematic synthesis and dual analytical approach offer new conceptual clarity and practical insights for researchers and policymakers. The detailed discussion of the study's novelty and added value is presented in Section 4.2. Scientific contribution.

Regarding the burgeoning significance of SA-FSCs in the current decade, this bibliometric analysis aims to investigate the academic landscape of this domain. This approach evaluates research quantitatively via mapping visually structures a field through documents, authors, and keywords. These methods reveal evolutionary trends, collaborations, and emerging fronts, complementing qualitative reviews. Further, integrating co-word and co-citation analyses provides insights into themes, foundational and influential themes, and conceptual links, helping scholars assess past, present, and future directions to guide academic strategies [24,38,40]. Through a comprehensive examination of publication patterns, this study endeavors to delineate the evolution of the SA-FSCs realm. Within this context, the central question that guides this study is: What are the prevailing themes, emerging trends, and foundational and influential themes in SA-FSCs research during the 2020s, and how might they shape future developments? Bibliometric perspectives offer a window into the evolution, current state, and future trends of SA-FSCs research, enabling the identification of scholarly pathways, gaps, and influences. Consequently, this paper departs from the following research questions (RQs):

RQ1: What is the significance of integrating digital technologies into A-FSCs during the 2020s?

RQ2: What are the prevailing themes and emerging trends characterizing SA-FSCs during the 2020s?
RQ3: What are the foundational and influential themes and topics within the field of SA-FSCs during the 2020s?

2. Methodology

2.1. Bibliometric approach

To answer the RQs, we adopted a three-step methodological approach which includes bibliometric, co-word, and co-citation analyses [38,41,42]. Bibliometric analysis quantitatively identifies, describes, and evaluates published research [24]. Bibliometric mapping visually represents a field's intellectual structure by classifying and mapping bibliographic elements like documents, authors, and keywords, elucidating relationships between disciplines, topics, and individual works [43,44]. This data-driven approach objectively uncovers a field's evolutionary patterns, collaboration networks, and research fronts [40,44]. Complementing qualitative reviews, rigorous bibliometric studies synthesize vast literature, pinpoint gaps, and position novel contributions, advancing specific research domains through systematic quantitative analysis of bibliographic big data [40,45]. The synergistic application of co-word and co-citation analysis techniques provides researchers with a multifaceted perspective on the dynamics of a research field. This dual approach enables the identification of emerging themes, foundational and influential themes, and the interconnections between various concepts and ideas. Consequently, scholars can gain insights into the past trajectories, current state, and potential future directions of a research domain, thereby facilitating informed decision-making and strategic planning in academic endeavors [38].

2.2. Data collection

Data collection was conducted using the Scopus database, with the search focused on the 'topic' field, encompassing titles, abstracts, and keywords of published documents. Three distinct groups of keywords were identified through a brainstorming session and a comprehensive literature review [24,34,46]. Group A comprised keywords about the agri-food research domain, while Group B encompassed keywords related to the supply chain research field. Group C consisted of keywords associated with the smart field of research, as shown in Table 2. The keywords within each group were combined using the Boolean operator "OR," whereas the groups themselves were linked through "AND."

2.3. Screening process

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocols (PRISMA-P) framework for the screening process in this study (Fig. 2). The PRISMA-P framework comprises a 17-item checklist to facilitate the preparation and reporting of robust systematic review protocols [47]. The search was limited to articles published since January 1, 2020, until May 13, 2024, excluding other document types. To ensure linguistic coherence, only articles written in English were considered. In this regard, from among 14,513 articles that were identified solely through the search string mentioned in Table 3 and without applying any filters, 11,179 articles were subsequently excluded due to a lack of sufficient eligibility for analysis based on the research protocol, following the application of the filters specified in Table 3. This rigorous screening process yielded a compilation of 3334 documents deemed eligible for in-depth bibliometric analysis. Given the interconnected nature of SA-FSCs, this study adopted a comprehensive search strategy to avoid fragmented analysis of isolated components (e.g., specific technologies or supply chain stages). The authors prioritized selecting an optimal set of documents that holistically addresses the system's complexity while ensuring analytical accuracy. This approach balanced inclusivity with methodological rigor, capturing diverse facets critical to future research and enabling systematic synthesis within a structured academic framework. A detailed breakdown of the data collection and screening procedure is presented in Table 3.

Table 2
Determination and grouping of study keywords.

Group A	Group B	Group C
Agri-food "Agricultur*", "Agrifood", "Food", "Agri-product*"	Supply Chain "Supply chain*", "Value chain*", "Logistic*"	Digitalization "Digit*", "Smart*", "Intelligen*", "Information syst*", "Data analy*", "Big data", "Techno*", "Artificial Intelligence", "Internet of Things", "Social media", "Blockchain*", "ICT"

The asterisk (*) attaches to the stem of a word and searches for any word which includes that stem, or the letters before the asterisk.

2.4. Analyzing the data

The data analysis process encompassed three main procedures. Firstly, descriptive statistics were generated from the Scopus database using version 4.2.1 of the Bibliometrix R-Tool. Bibliometrix is an R-package designed for comprehensive bibliometric and scientometric analysis, integrating with other R packages for data manipulation, calculations, and visualizations [48]. The key descriptive statistics included annual scientific production, annual percentage growth rate, international co-authorships, most prolific authors, leading journals, and top countries in terms of document count and citations. In the second phase, co-word and co-citation analyses were performed using version 1.6.20 of the VOSviewer software. VOSviewer is a specialized program for creating and visualizing bibliometric maps, with a focus on effective graphical representation of large bibliometric networks [43].

2.4.1. Keyword co-occurrence analysis

To explore the conceptual structure and research trends within the field, a keyword co-occurrence analysis (Co-word analysis) was conducted. Co-word analysis, a bibliometric technique, assesses the frequency and co-occurrence of keywords within a corpus of documents, predicated on the notion that frequently co-occuring keyword combinations signify specific research topics or themes [38]. As a bibliometric method, co-word analysis facilitates insights into the structure and dynamics of scientific fields by analyzing the co-occurrence of keywords in the literature. This approach is useful for exploring complex interactions and emerging trends within a research domain [49]. This study employed co-word analysis on index keywords (keywords plus) extracted from the Scopus database. Specifically, the full counting method, which assigns equal weight to each co-occurrence instance, was performed and the relatedness of keywords was determined based on the number of documents in which they co-occurred. From the initial set of 12,707 index keywords, those occurring at least 25 times were selected, and off-topic keywords were discarded. The resulting network visualization comprised 134 keywords organized into five distinct clusters. The node size (circles) represents the weight or importance of each keyword, while the links (lines) indicate relationships between keywords, with thicker lines denoting stronger connections. Finally, different colors correspond to the distinct research clusters to which the keywords belong [50].

2.4.2. Co-citation analysis

Co-citation analysis, a prominent bibliometric technique, quantifies the frequency at which two publications are referenced jointly by a third publication [51,52]. This metric unveils the conceptual proximity and semantic relatedness between research documents based on their co-citation linkages. Highly co-cited papers signify pivotal concepts, methodologies, or theories that have garnered substantial peer recognition and exerted significant influence within a discipline [53]. By mapping these co-citation patterns, the intellectual structure and

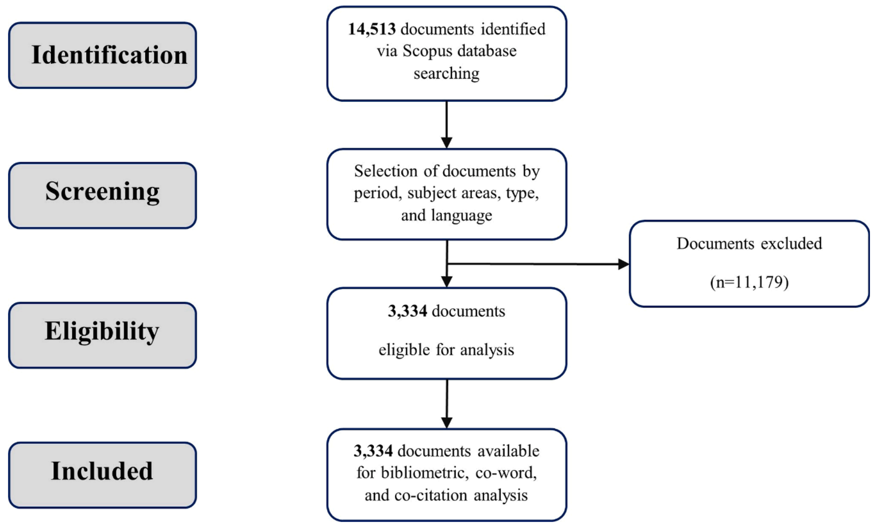

Fig. 2. Document selection protocol based on the PRISMA-P approach.

Table 3
Research screening protocol.

Search string	**TITLE-ABS-KEY** (“Agricultur*” OR “Agrifood” OR “Food” OR “Agri-product*”) **AND** (“Supply chain*” OR “Value chain*” OR “Logistic*”) **AND** (“Digit*” OR “Smart*” OR “Intelligen*” OR “Information Syst*” OR “Data analy*” OR “Big data” OR “Techno*” OR “Artificial Intelligence” OR “Internet of Things” OR “Social media” OR “Blockchain*” OR “ICT”)
Subject areas	“Agricultural and Biological Sciences”, “Environmental Science”, “Engineering”, “Computer Science” and “Business, Management, and Accounting”
Document type	Journal articles in English
Period	1 January 2020–13 May 2024
Database	Scopus

The asterisk (*) attaches to the stem of a word and searches for any word which includes that stem, or the letters before the asterisk.

knowledge epicenters of a field can be delineated. Moreover, co-citation analysis elucidates the interconnectivity of diverse research domains, illuminating the synergistic cross-pollination of ideas across disciplinary boundaries [51]. This study employed co-citation analysis on cited references of articles extracted from the Scopus database. Specifically, the full counting method was employed for the co-citation analysis, assigning equal weight to each co-citation instance. The relatedness between cited references was determined by the number of documents in which they were co-cited together. Out of 178,249 total cited references, those with a minimum citation count of 11 were selected. The network visualization represented 100 cited references clustered into four groups, where the circle size corresponds to the weight of cited references, lines indicate the linkages between two references, line thickness represents the strength of connection, and distinct colors signify different research clusters to which the cited references belong [50]. To ensure a focused and in-depth analysis of each co-citation derived cluster, the 10 articles exhibiting the highest total link strength were selected from each cluster (resulting in a total of 40 articles across all clusters). The content within these articles was subsequently scrutinized and analyzed. Ultimately, based on this thorough analysis, two research fields were defined and proposed for each cluster. This was achieved first by synthesizing the collective outcomes and conclusions reported in each study, and second by aggregating all stated recommendations for future work. Through this analysis, it was possible to discern and define the research fields for each cluster.

3. Results and discussion

3.1. Bibliometric analysis

This analysis elucidated the significance of integrating digital technologies into A-FSCs. Findings demonstrated that the SA-FSCs have emerged as significant research areas in the current decade, as evidenced by the growing number of publications shown in Fig. 3 and Table 4. This development holds substantial implications for researchers and practitioners in this field. The present bibliometric study analyzed a comprehensive collection of 3334 documents from 1067 distinct sources (journals), authored by 12,948 researchers over five years (2020–2024). On average, each document received approximately 14.09 citations. The descriptive statistics revealed that individual authors published an average of 0.257 documents, with an average of 1.38 co-authors per document. Notably, the percentage of international co-authorship in the production of these documents was approximately 32.69 %, indicating a significant level of global collaboration in this research domain. The annual growth rate in the publication of documents related to SA-FSCs during the study period was around 27.65 %. This growth trend exhibited a linear relationship, suggesting a consistent and increasing importance of this research topic throughout the current decade. Significantly, as shown in Fig. 4, the number of documents published from the beginning of 2020 to May 13, 2024 (3334 documents) is approximately 1.5 times the total number of documents published from the inception of research in this field (1976) until the beginning of the current decade (2216 documents). This finding highlights the substantial surge in research activity related to SA-FSCs in the current decade. The results of this bibliometric analysis underscore the growing attraction and importance of SA-FSCs and their applications in the current decade.

Appendix A1 presents the top 10 most productive authors who have contributed significantly to the field of SA-FSCs, along with their respective h-indices. The h-index is a metric that balances the number of published articles and the citations received by those articles, thereby serving as a useful indicator of a researcher's impact and influence within a given domain [54].

The geographic distribution of published research outputs related to SA-FSCs, as depicted in Appendix A2, reveals a dominant contribution from authors affiliated with universities in China. This pattern aligns with China's position as a major agricultural producer and its concerted efforts to improve it [55]. Following China, India emerges as a significant contributor to this field, with approximately half the number of publications compared to its counterpart. Other notable countries

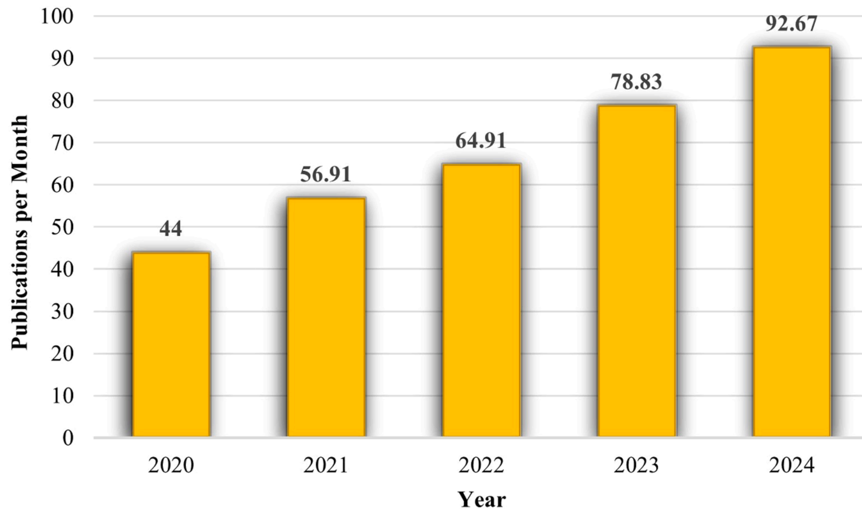

Fig. 3. Average monthly publications covering the research field in different years.

Table 4
Overall information on the bibliometric analysis.

Overall data	
Documents	3334
Journals (Sources)	1067
Author's keywords	9600
Keywords Plus	12,707
Average citations per document	14.09
Authors	12,948
Documents per author	0.257
Authors per document	3.883
Co-Authors per document	4.38
International co-authorships %	32.69
Annual Growth Rate %	27.65
Years	2020–2024

actively engaged in research related to SA-FSCs include the US, Italy, and the UK. However, evaluating the impact and quality of research outputs extends beyond mere quantitative measures of publication counts. In this regard, authors from Spanish universities and institutions have demonstrated exceptional influence, garnering the highest citation counts for their published works among the countries analyzed; Despite having a relatively lower number of publications. Closely following Spain, researchers from the UK and the US have also made significant contributions, as evidenced by their competitive citation metrics. This pattern highlights the global nature of research efforts in this domain and the collaborative endeavors undertaken by scholars from various regions to advance knowledge and drive innovations in SA-FSCs.

Fig. 5 presents an analysis of international collaboration patterns in the field of SA-FSC research. It illustrates the number of articles published by authors from a single country (Single Country Publications-SCP) and those authored by researchers from multiple countries (Multiple Country Publications-MCP), categorized by the corresponding author's country affiliation. Notably, while China and India are the most prolific producers of research outputs in this domain, they exhibit relatively lower levels of international collaboration. A substantial proportion of the articles originating from these countries are authored solely by researchers within their respective national boundaries. Conversely, countries such as England and Australia, despite having a comparatively smaller overall output in this field, demonstrate a high degree of international participation, with approximately half of their published articles involving co-authors from different countries. By fostering global partnerships and leveraging the collective expertise of researchers from diverse regions, the global research community can

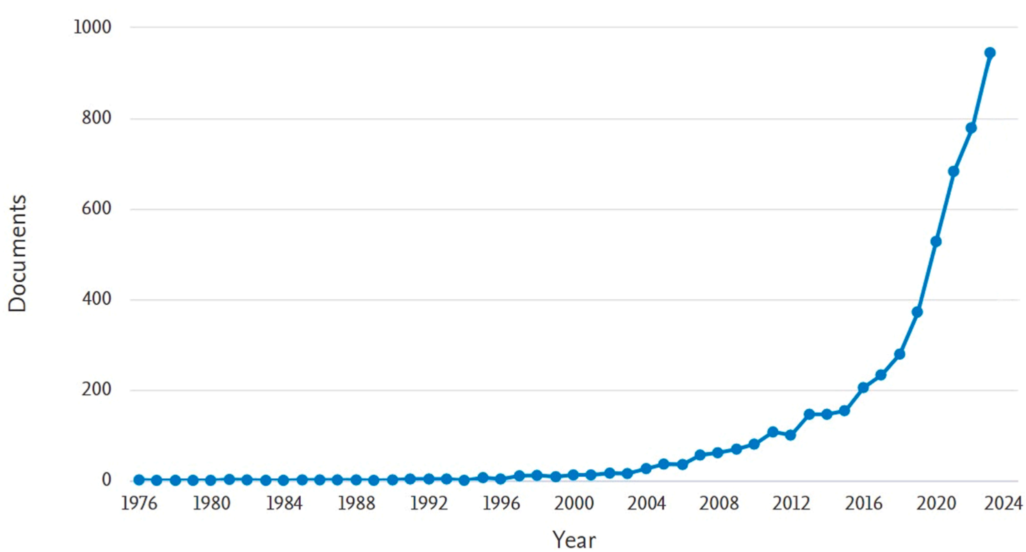

Fig. 4. Annual trend in the number of publications covering the research field.

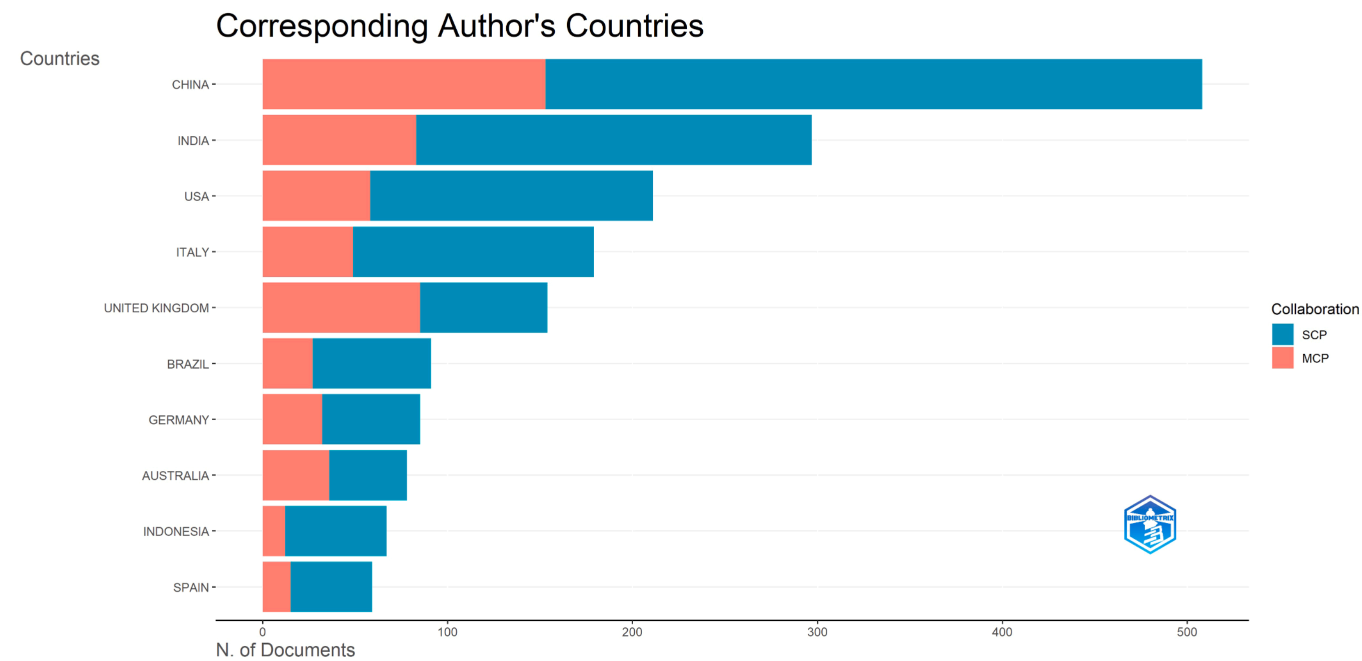

Fig. 5. Research international collaboration patterns based on the corresponding author's country.

accelerate progress, drive innovation, and develop holistic solutions that transcend national boundaries, ultimately enhancing the resilience, efficiency, and sustainability of A-FSC operations worldwide.

Appendix A3 reports the top 10 journals that have published the documents analyzed in this study, along with their respective overall information. The journals with the highest number of published articles are Sustainability (191), Journal of Cleaner Production (88), and IEEE Access (65). These three journals have also received the highest citation counts for their published works in this field. Notably, while the Journal of Cleaner Production and IEEE Access have fewer published articles compared to Sustainability, they have achieved a higher number of citations per published document, indicating the significant impact and influence of their contributions to the field of SA-FSC research. Appendix A3 further provides information related to the quality of these journals, including their publishers, citation metrics, rankings, and impact factors. All of the top 10 journals, except for the International Journal of Environmental Research and Public Health, are ranked in the first quartile (Q1) based on the Scimago Journal Rank (SJR), underscoring the high quality of the publications dedicated to this research domain.

A noteworthy observation is the emerging prominence of Multidisciplinary Digital Publishing Institute (MDPI) journals in the field of publishing articles related to the SA-FSCs. In contrast to a similar study conducted by Rejeb et al. [34], which investigated the same topic from 1997 to mid-2021 and found that 6 out of the top 10 journals were from the Elsevier database, the analysis of the current research in the first five years of the current decade reveals a shift. Among the top 10 journals publishing documents in this field, 6 journals are now from the MDPI database, while only one journal is from the Elsevier database. This transition in the leading journal publishers highlights the dynamic nature of the research landscape and the evolving preferences and priorities of researchers in disseminating their findings within the realm of SA-FSC.

3.2. Co-word analysis

This analysis uncovered prevailing themes and emerging trends in the realm of SA-FSCs. Through the network analysis, a total of 134 index keywords were extracted from the reviewed documents. These keywords were analyzed to determine their frequency and construct a network model. As shown in Table 5, which illustrates the top ten Keywords Plus, “supply chains” emerged as the most recurrent keyword, appearing 591 times. This finding underscores the centrality of supply chain management and optimization in the research domain of intelligent food-agriculture systems. Notably, several of the top 10 keywords, such as “sustainability” and “sustainable development", are directly linked to sustainability considerations. This pattern highlights the significant emphasis placed on integrating sustainability principles into the SA-FSCs. Achieving sustainability necessitates a balanced approach that harmonizes economic growth, environmental protection, and social imperatives. Consequently, the development of management policies firmly rooted in the sustainable development framework becomes crucial [16,56]. Additionally, the prominence of the keyword “food safety” among the most frequent terms underlines the critical role of SA-FSC systems in ensuring a reliable and adequate food supply for global populations. Food safety, a key element governed by national and international regulatory frameworks, emerges as an essential factor in guaranteeing the safety and security of the FSC [57]. However, the increasing complexity of global food supply networks, coupled with emerging threats such as climate change and urbanization, can potentially give rise to food safety risks that pose significant challenges to the resilience and integrity of these intricate systems [58].

Fig. 6 presents a network visualization of keyword co-occurrence in the reviewed documents spanning the first five years of the current decade (2020–2024). The visualization prominently features the top 10 keywords listed in Table 5. The occurrence metric refers to the multiple

Table 5
Top 10 most frequent index keywords among analyzed documents.

Keywords Plus	No. occurrences/frequency
Supply chains	591
Food supply	405
Supply chain management	343
Agriculture	256
Blockchain	246
Sustainable development	232
Decision making	180
Internet of things	174
Sustainability	158
Food safety	133

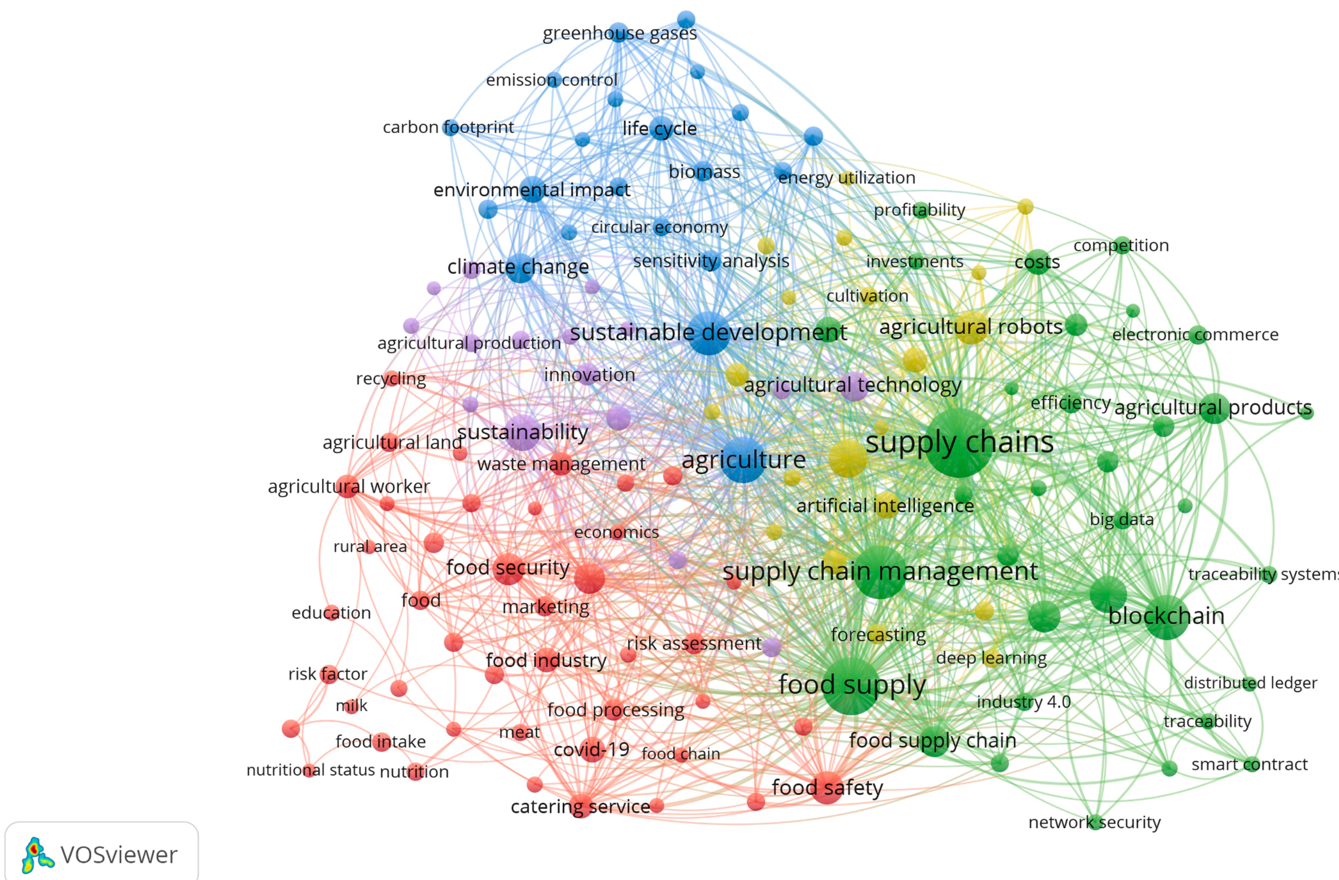

Fig. 6. Network visualization of keyword co-occurrence analysis.

appearances of a keyword across different articles, while the link value indicates the number of connections associated with a specific keyword about others. The total link strength represents the aggregation of link strength values for a particular keyword [24,59]. Table 6 summarizes the identified clusters, their respective themes, and the most frequent keywords within each cluster.

The network analysis comprises five distinct clusters, each with a specific focus: “Food Safety and Food Waste” (red cluster), “A-FSC Management and Traceability” (green cluster), “Sustainable Development in A-FSCs” (blue cluster), “Digital Technologies in A-FSCs” (yellow cluster), and “Innovation and Technology Adoption in A-FSCs” (purple cluster).

The red cluster, titled “Food Safety and Food Waste,” encompasses studies that analyze the complex and multifaceted challenges associated with food safety and food waste management within the A-FSCs (43 Publications). Keywords such as “food safety,” “food security,” “COVID-19,” and “agricultural land” are indicative of research efforts aimed at ensuring food security throughout the A-FSC, exploring various strategies and approaches to achieve these objectives. Food security necessitates a comprehensive and multidimensional approach, encompassing social protection measures as well as the provision of healthy and nutritious food. Transformative changes within existing food systems are essential to establish a more equitable and sustainable society, as food safety is an integral component of food security [60]. Each stage of the supply chain presents existing or potential risks that can compromise food safety, extending beyond food production and processing to encompass raw materials, food circulation and storage, and points of consumption such as supermarkets and restaurants, as well as food packaging [61,62]. Consequently, enhancing food safety requires a holistic approach that spans the entire supply chain, ensuring that food remains safe from the beginning to the end of the chain. Additionally, keywords such as “food waste” and “waste management” are indicative of studies that investigate strategies for preventing food waste throughout the A-FSC. According to the Food and Agriculture Organization (FAO), approximately 33 % of the food produced globally is wasted at various stages of the supply and consumption process, highlighting the importance of incorporating recycling practices into the design of sustainable food chain systems [63]. Wasted food generates 8–10 % of global greenhouse gas emissions, alongside significant water, land, and biodiversity impacts, underscoring the urgency of UN Sustainable Development Target 12.3 to halve food waste by 2030. Digital technologies like IoT, AI, and platforms show promise in reducing waste across the A-FSCs, optimizing production, enabling dynamic pricing, and redistributing surplus. However, their quantifiable sustainability impacts remain underexplored [64]. Food waste simultaneously increases production, distribution, and disposal costs while contributing to the depletion of water, energy, land, and other natural resources. Therefore, the primary objective of food waste management is to minimize the resulting negative environmental, social, and economic impacts [65]. Keywords such as “food industry,” “food processing,” “marketing,” and “logistics” are relevant to both food security and food waste management issues within the A-FSC. Based on the thematic focus of this cluster, the following targeted future research directions are proposed: a) Evaluate AI-based dynamic pricing to reduce waste; and b) Quantify IoT-driven cold chain monitoring impacts for A-FSCs.

The green cluster, titled “A-FSC Management and Traceability,” encompasses studies that explore various strategies for optimizing and managing the A-FSC (34 Publications). Keywords such as “costs,” “commerce,” “sales,” and “efficiency” are indicative of research efforts focused on the economic aspects of supply chain management. Another critical aspect of optimal supply chain management is the implementation of traceability systems. Keywords such as “blockchain,”

Table 6
Prevailing themes in SA-FSCs (Clusters based on co-word analysis).

Cluster	Theme	Most Frequent Keywords
1 (Red)	Food safety and Food waste	Food safety; Food security; Food waste; Covid-19; Food industry; Catering service; Agricultural worker; Waste management; Food processing; Risk management; Marketing; Procedures; Agricultural land; Logistics; Food
2 (Green)	A-FSC management and traceability	Supply chains; Food supply; Supply chain management; Blockchain; Internet of things; Digital storage; Food supply chain; Agricultural products; Costs; Commerce; Sales; Information management; Efficiency; Quality control; Agricultural supply chains; Big data; Traceability systems; Smart contract
3 (Blue)	Sustainable development in A-FSCs	Agriculture; Sustainable development; Climate change; Environmental impact; Life cycle; Sensivity analysis; Greenhouse gases; Biomass; Economic and social effects; Land use; Environmental technology; Fertilizers; Gas emissions; Carbon footprint
4 (Yellow)	Digital technologies in A-FSCs	Desicion making; Agricultural robots; Artificial intelligence; Crops; Machine learning; Farms; Forecasting; Learning systems; Deep learning; Cultivation; Forestry; Optimazation; Smart agriculture; Developing countries; Algorithms
5 (Purple)	Innovation and technology adoption in A-FSCs	Sustainability; Agricultural technology; Technology adoption; Innovation; Stakholder; Food production; Small holder; Agricultural production; Alternative agriculture; Value chains; Agroindustry; Farming system; Agricultural development

"digital storage," "information management," "big data," "traceability systems," and "smart contract" are associated with studies that investigate the transparency and tracking of various products throughout the A-FSC. Traceability has emerged as a foundational principle within supply chain management. Governments worldwide are increasingly enacting regulations that necessitate its integration to uphold product safety and preserve consumer welfare. Traceability enables the availability of information about the product throughout its lifecycle, including the production stage, raw materials, semi-finished products, and finished products, to both producers and consumers through the utilization of information and communication technologies (ICT) [66,67]. Among the tracking technologies employed in the A-FSCs, blockchain technology is one of the most reliable and innovative solutions. Blockchain technology utilizes a decentralized digital ledger comprising chronologically recorded and cryptographically secured blocks of transactions arranged in a chained format. Its capability to facilitate the sharing of information across a distributed network while generating an unalterable, traceable, and transparent chronicle of past transactions renders blockchain an appealing solution to underpin supply chain traceability (SCT) systems [68,69]. Based on the thematic focus of this cluster, the following targeted future research directions are proposed: a) Blockchain–IoT integration for perishable goods; b) Cost optimization for traceability systems in A-FSCs.

The blue cluster, titled "Sustainable Development in A-FSCs," comprises studies that have aimed to optimize the A-FSCs by integrating principles of sustainable development (21 Publications). Sustainable development is underpinned by three main pillars: environmental, economic, and social [70,71]. Keywords such as "climate change," "environmental impact," "greenhouse gases," "biomass," "land use," "environmental technology," "fertilizers," "gas emissions," and "carbon footprint" predominantly address the environmental aspects of sustainable development within the context of the A-FSCs. Concurrently, keywords like "life cycle" and "economic and social effects" encompass the economic and social dimensions of sustainable development concerning supply chain operations. Therefore, it is evident that all three facets of sustainable development must be considered simultaneously and coordinated to effectively develop and optimize A-FSCs. Based on the thematic focus of this cluster, the following targeted future research directions are proposed: a) Model energy optimization in A-FSCs for lower carbon footprint; and b) Developing circular economy in A-FSCs.

The yellow cluster, titled "Digital Technologies in A-FSCs," encompasses studies that explore the utilization of cutting-edge technologies to enhance various stages of the A-FSC (20 Publications). Digital technologies refer to the electronic apparatus, platforms, instruments, and resources that possess the capabilities to generate, store, or process data [72]. The keywords "agricultural robots" and "smart agriculture" are associated with the manufacturing stage of SA-FSC, commonly referred to as smart farming. The concept of smart farming (SF) has transitioned from an approach solely dependent on human knowledge and empirical experience to one that integrates scientific principles, technological advancements, and data specific to the domain [73]. Meanwhile, keywords such as "decision making," "artificial intelligence," "machine learning," "learning systems," "deep learning" and "algorithms" are applicable across all stages of the supply chain. In the current dynamic and volatile business landscape, supply chains must possess the capability to expedite product development cycles, rapidly launch new products, and promptly adapt to fluctuating demand and diverse customer requirements. Consequently, the integration of A-FSCs with emerging technologies, as highlighted in this cluster, can exert a profound influence on enhancing decision-making processes and optimizing and streamlining supply chain operations [74]. As an illustrative example, the manufacturing stage within a smart farming system necessitates the employment of multiple data processes and advanced technologies to generate insightful information. Internet of Things (IoT) devices are leveraged for digital data acquisition, enabling the capture of real-time field conditions. Subsequently, machine learning techniques, and more recently, deep learning algorithms, are applied to analyze the acquired data [75]. Based on the thematic focus of this cluster, the following targeted future research directions are proposed: a) Compare deep learning models for crop yield prediction; b) Develop real-time IoT alerts in A-FSCs like pest outbreaks.

The purple cluster, entitled "Innovation and Technology Adoption in A-FSCs," encompasses scholarly works that investigate the adaptation and implementation of novel technologies within the context of A-FSCs (16 Publications). The keywords "technology adoption," "innovation," and "agricultural development" pertain to the integration and utilization of modern technological advancements across various stages of the supply chain continuum. Numerous intrinsic and extrinsic factors exert influence on the adaptation of emergent technologies at distinct junctures of the supply chain, and by accurately identifying and favorably positioning these determinants, effective strategic measures can be undertaken towards optimizing the management of A-FSC operations [76,77]. Keywords such as "agricultural technology," "food production," "smallholder," "agricultural production," "alternative agriculture" and "farming system" place a predominant emphasis on the adaptation and appropriate application of modern technological innovations within the manufacturing stage of the A-FSC. This stage is regarded as one of the most critical stages of the A-FSC, as it involves the transformation of raw materials with lower intrinsic value into value-added products suitable for human consumption. Consequently, the optimization of this phase through the implementation of novel methodologies and technological interventions will yield a profound impact on the entire supply chain ecosystem [78]. Based on the thematic focus of this cluster, the following targeted future research directions are proposed: a) Examine smallholder adoption barriers to SA-FSCs; b) Developing national agendas for implementing SA_FSCs.

The overlay visualization of the keyword co-occurrence analysis (Fig. 7) reveals that keywords such as "smart contract," "distributed ledger," "Industry 4.0," "deep learning," "digital storage," "smart agriculture," "circular economy," "network security," "farms," and "emission control" have been more extensively utilized in recent research on the A-FSC. Concurrently, these keywords exhibit a relatively low

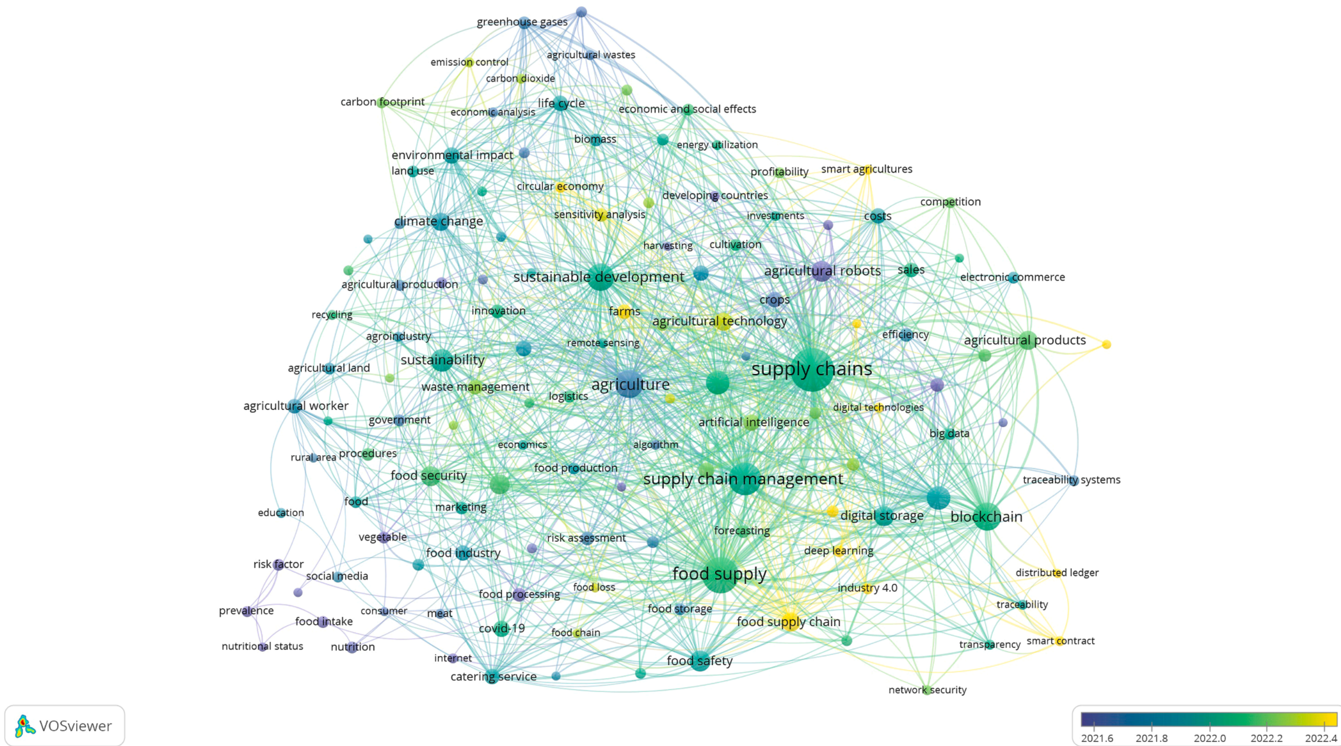

Fig. 7. Overlay visualization of keyword co-occurrence analysis.

Table 7
The most foundational and influential works (Top 10 co-cited references).

No.	Documents	Citation	Total link strength	Link
1	Galvez et al. [116]	30	277	78
2	Saberi et al. [117]	48	263	74
3	Feng et al. [118]	34	247	75
4	Salah et al. [103]	63	245	72
5	Bumblauskas et al. [119]	28	243	79
6	Shahid et al. [101]	38	214	72
7	Zhao et al. [120]	32	212	74
8	Kamble et al. [121]	31	206	75
9	Lin et al. [105]	49	205	62
10	Behnke and Janssen [112]	19	205	71

number of connections with other keywords, indicating their novelty and potential for further exploration in these domains. By comparing Figs. 6 with 7, it becomes evident that the keywords or features appear to be more novel and emerging within the green (A-FSC Management and Traceability) and yellow (Digital Technologies in A-FSCs) clusters. This observation underscores the growing importance of emerging technologies and novel technological advancements in enhancing the management, traceability, and efficiency of A-FSCs in recent years.

3.3. Co-citation

This analysis explored the foundational and influential themes of SA-FSCs. To conduct this analysis, a set of 100 publications (references) was extracted from the reference lists of the studied documents. This subset was analyzed to quantify the co-citation counts and construct a network model representation. Table 7 presents the 10 most co-cited references based on their total link strength values. Compared to others, these studies exhibit the highest degree of cross-referencing, suggesting their influential and seminal role in advancing the research topic under investigation to date. An inspection of the titles listed in Table 7 reveals that all of the highly co-cited articles pertain to blockchain technology and its applications, particularly in the context of traceability within A-FSCs. This observation underscores the significance of this emerging technology for enabling sustainable SA-FSC systems in the contemporary era.

Fig. 8 shows the network visualization of the co-citation relationships among the references analyzed in this study. The top 10 co-cited references identified in Table 7 are prominently visible within this network representation, further corroborating their central position and impact within the literature landscape explored. The identified clusters represent groups of publications that exhibit thematic coherence and interconnectivity. Publications within the same cluster, denoted by nodes of the same color, share common topical foci, indicating a convergence of research themes and concepts [38].

The co-citation analysis is comprised of four clusters: “Sustainable A-FSC management” (red cluster); “Blockchain applications in A-FSCs” (green cluster); “Blockchain-based solutions for agri-food safety and traceability” (blue cluster); and “Challenges and requirements of blockchain adoption in A-FSCs” (yellow cluster).

Cluster 1 (red), titled “Sustainable A-FSC management” comprises a total of 38 publications. The agri-food sector is witnessing a growing emphasis on the principles of sustainability and supply chain transparency, driven by the rapid industrialization of agricultural practices, surging global food demand, and heightened concerns surrounding food quality and safety [79]. The cluster centers on achieving sustainability through waste reduction, integrated traceability, and overcoming governance and digitalization challenges. Research has emphasized waste minimization as paramount. Govindan [80] and Kamble et al. [81] have advocated for circular economy strategies, such as repurposing food waste, and data-driven forecasting to align supply with demand and prevent spoilage. Crucially, traceability has been framed not as a standalone function but as an intrinsic element of logistics management [82,83], essential for safety, quality control, and waste reduction. However, implementing effective traceability faces significant hurdles, particularly high costs and technological interoperability issues for SMEs, as Regattieri et al. [84] identified. Digital technologies like IoT and big data have been identified as critical enablers for real-time monitoring and resilient operations [85,86]. Yet, Badia-Melis

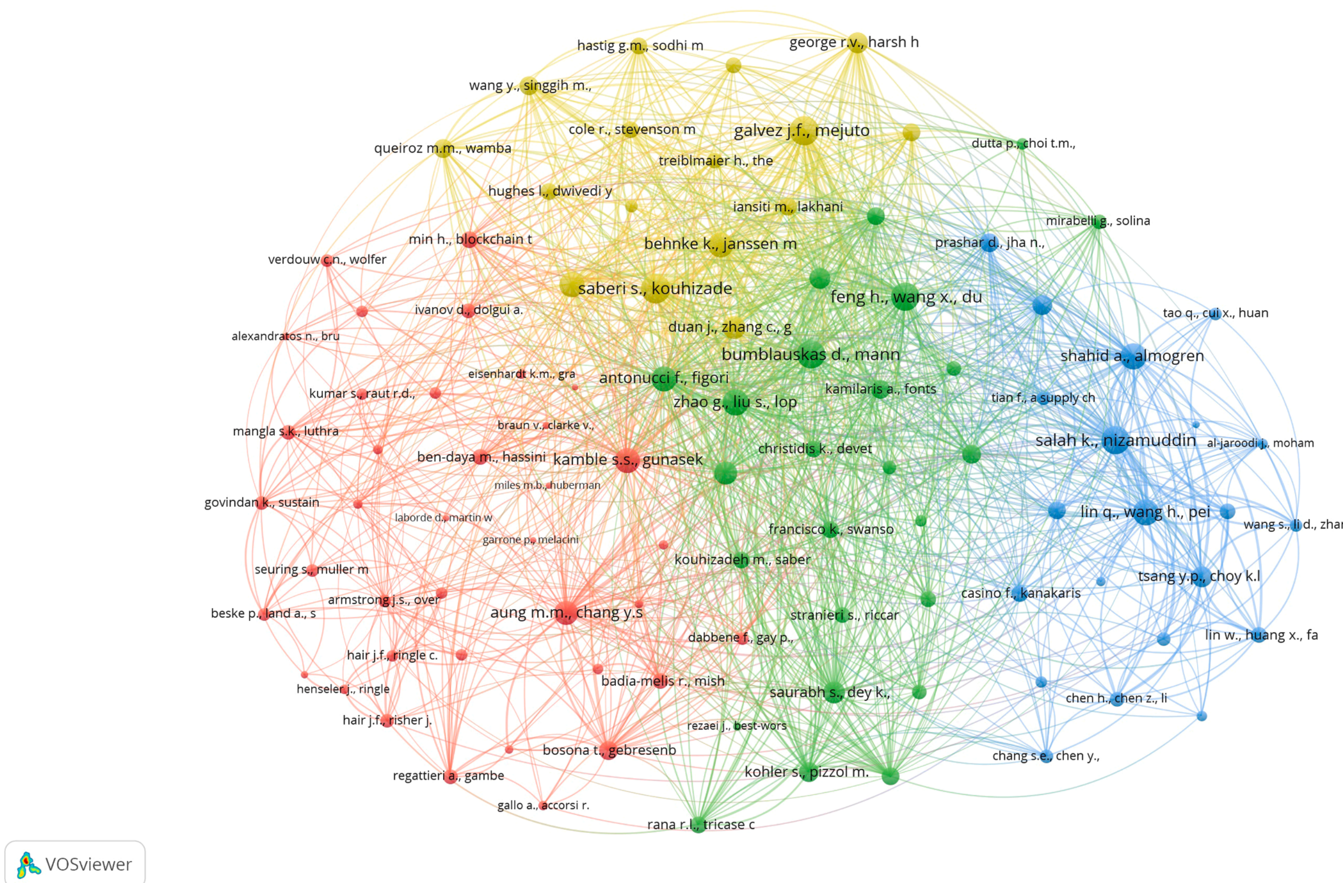

Fig. 8. Network visualization of co-citation analysis.

et al. [87] have pointed to persistent flaws in coordinating real-time data flows across complex chains. Governance has emerged as a critical tension point. Mangla et al. [79] have revealed power imbalances where large retailers impose sustainability standards without cost-sharing mechanisms, while Min [88] identified gaps where policy pressures lack accompanying technical or financial support for SME compliance. Collectively, the literature reveals a fundamental tension between the potential of digital tools and circular models for sustainability and the practical barriers of cost, fragmented implementation, and unequal power dynamics within the supply chain. Therefore, future research must prioritize a) Developing circular smallholder-inclusive models and b) Co-creating localized social sustainability metrics to address equity and scalability gaps inherent in current approaches.

Cluster 2 (green), titled “Blockchain applications in A-FSCs” comprises a total of 25 publications. Early foundational work [89–91] established blockchain’s core principles (like decentralization, immutability, and transparency) and its nascent potential for secure transactions and data sharing beyond finance, including supply chain integration and IoT device coordination. This shifted towards sector-specific application studies, emphasizing traceability and transparency as primary drivers [92–94]. Research has consistently identified blockchain’s capacity to mitigate fraud, enhance food safety, verify ethical sourcing (e.g., conflict minerals and fair labor), and improve recall efficiency by providing an immutable, shared ledger accessible across stakeholders. A significant thematic strand focuses on adoption drivers and barriers. Kamble et al. [93] have applied integrated technology adoption models (TAM,[1] TPB,[2] TRI[3]) in the Indian context, finding perceived usefulness, attitude, and behavioral control as key adoption drivers, while technology discomfort and insecurity were surprisingly insignificant. Francisco and Swanson [95] have employed UTAUT,[4] highlighting performance expectancy and facilitating conditions. However, multiple papers have revealed persistent challenges hindering widespread implementation including high implementation costs, scalability limitations, interoperability issues with legacy systems and diverse IoT/RFID technologies, data privacy concerns, lack of standardization, regulatory uncertainty, and significant knowledge gaps, particularly among SMEs[5] [93,96–98]. The complexity of integrating blockchain with complementary technologies (IoT sensors, AI analytics) for real-time data capture and actionable insights has been identified as a recurring technical hurdle. Sustainability has emerged as a critical late-stage theme, linking blockchain-enabled traceability to ethical consumption, reduced waste, environmental monitoring, and achieving SDGs[6] [96,97]. Studies on specific sub-sectors like halal food [96] and grape wine [98] have demonstrated the need for tailored solutions addressing unique certification and integrity requirements, while also highlighting the potential for disintermediation and enhanced consumer trust through verifiable provenance. Consequently, future efforts should prioritize a) Developing standardized IoT-blockchain integration frameworks for perishables and designing

[1] Technology Acceptance Model
[2] Theory of Planned Behavior
[3] Technology Readiness Index
[4] Unified Theory of Acceptance and the Use of Technology
[5] Small and Medium Enterprises
[6] Sustainable Development Goals

Table 8
Foundational and influential themes of SA-FSCs (Clusters based on co-citation analysis).

Cluster	Cluster lable	Number of ducuments	Representative publications
1 (Red)	Sustainable A-FSC management	38	Armstrong and Overton [122]; Aung and Chang [82]; Badia-Melis et al. [87]; Ben-Daya et al. [85]; Beske et al. [123]; Bosona and Gebresenbet [83]; Dabbene et al. [124]; Govindan [80]; Hair et al. [125]; Ivanov et al. [86]; Kamble et al. [81]; Mangla et al. [79]; Min [88]; Regattieri et al. [84]; Rogers [126]
2 (Green)	Blockchain applications in A-FSCs	25	Abeyratne and Monfared [89]; Ali et al. [96]; Antonucci et al. [92]; Bumblauskas et al. [119]; Christidis and Devetsikiotis [90]; Feng et al. [118]; Kamble et al. [93]; Kamilaris et al. [127]; Köhler and Pizzol [128]; Kouhizadeh et al. [129]; Nakamoto [91]; Rana et al. [97]; Sander et al. [94]; Saurabh and Dey [98]; Zhao et al. [120]
3 (Blue)	Blockchain-based solutions for agri-food safety and traceability	21	Casino et al. [106]; Creydt and Fischer [107]; Lin et al. [105]; Lin et al. [100]; Perboli et al. [99]; Prashar et al. [130]; Salah et al. [103]; Shahid et al. [101]; Tsang et al. [104]; Zhang et al. [102]
4 (Yellow)	Challenges and requirements of blockchain adoption in A-FSCs	16	Behnke and Janssen [112]; Duan et al. [108]; Galvez et al. [116]; George et al. [110];; Kamble et al. [121]; Mao et al. [113]; Queiroz and Fosso Wamba [109]; Saberi et al. [117]; Wang et al. [111]

scalable and b) Low-cost consensus mechanisms accessible to SMEs to overcome current adoption bottlenecks and unlock the technology's full sustainable potential.

Cluster 3 (blue), titled "Blockchain-based solutions for agri-food safety and traceability" comprises a total of 21 publications. Collectively, these works have established blockchain as a transformative technology for enhancing transparency, immutability, and trust across SA-FSCs. The primary focus is overcoming critical challenges in traditional traceability systems including data fragmentation, vulnerability to tampering, lack of interoperability among diverse stakeholders, and insufficient response times during contamination events. Key contributions revolve around architectural frameworks integrating blockchain with complementary technologies. Perboli et al. [99] pioneered a lean methodology for designing real-world blockchain use cases, demonstrating cost savings and efficiency gains in fresh food logistics, while highlighting the critical success factor of stakeholder buy-in. Lin et al. [100] provided a comprehensive survey categorizing agricultural blockchain applications (provenance, smart farming data, and trade finance) and technical components, identifying persistent challenges like scalability and legacy system integration. Further, several papers have proposed specific end-to-end solutions. Shahid et al. [101] emphasized decentralized storage (IPFS[7]) and reputation systems for accountability. Zhang et al. [102] designed a multi-mode storage mechanism for grain hazard management; and Salah et al. [103] detailed Ethereum smart contracts for soybean traceability. A strong emphasis exists on practical implementation and performance. Tsang et al. [104] uniquely integrated IoT, fuzzy logic for quality decay evaluation, and a novel PoSCS[8] consensus mechanism tailored for perishable food traceability, addressing the mismatch of traditional crypto-centric consensus. Lin et al. [105] combined blockchain with EPCIS[9] standards, implementing enterprise level smart contracts and dynamic on-chain/off-chain data management to alleviate blockchain data bloat while ensuring security. Casino et al. [106] have validated their distributed model through a real dairy supply chain case study, developing functional smart contracts that demonstrated significant recall efficiency improvements and regulatory compliance. Finally, Creydt and Fischer [107] critically reviewed applications and limitations, stressing the persistent garbage-in/garbage-out problem concerning initial data input security and verification at the farm level. Despite the demonstrable benefits (enhanced auditability, reduced fraud, faster recalls, and potential cost savings) the analysis has revealed consistent limitations. Scalability remains a major technical hurdle for handling high-volume, granular traceability data. Furthermore, ensuring the veracity and trustworthiness of initial data entry points (e.g., farm records) into the immutable ledger is a significant unsolved challenge, as blockchain secures data after entry but cannot inherently validate real world events. These limitations collectively necessitate future work on a) Blockchain technology's role in reducing food injustice and malnutrition; and b) Automated IoT-audit integration protocols to bridge the physical-digital trust gap effectively.

Cluster 4 (yellow), titled "Challenges and requirements of blockchain adoption in A-FSCs" comprises a total of 16 publications. Blockchain technology is lauded as a transformative force poised to revolutionize A-FSC management, promising enhanced efficiency, transparency, and traceability [108,109]. Collectively, these works have identified a complex landscape of technological, organizational, and regulatory hurdles hindering widespread implementation, while acknowledging blockchain's transformative potential for traceability, transparency, and trust. The analysis reveals pervasive technological challenges as primary barriers. Scalability limitations and transaction latency [109–111], integration difficulties with legacy systems like IoT, and concerns over data security despite blockchain's inherent security features have been consistently highlighted. Furthermore, ensuring data accuracy at the point of origin remains a critical vulnerability [111–113]. Significant organizational and collaborative barriers emerge. Achieving multi-stakeholder consensus and participation across fragmented A-FSCs proves difficult due to competing interests, resistance to data sharing (especially sensitive commercial information), and lack of trust [108,111,112]. The absence of universal data standards and interoperability protocols between potential blockchain platforms creates further friction [109,112]. High implementation and maintenance costs, particularly for smaller actors, present substantial economic hurdles [109,111]. Regulatory and governance uncertainties compound these issues. Evolving and often fragmented regulatory landscapes across jurisdictions create compliance complexity [108,112,114]. Crucially, there's a lack of clear governance models for consortium blockchains; determining authority, decision-making processes, and liability frameworks remains unresolved [114,115]. Despite these challenges, the papers strongly affirm blockchain's potential value proposition. Further, several papers [108,110,113] have also explored integrating blockchain with analytics (e.g., AI and ML for quality prediction) and IoT for automated data capture. Consequently, future research must prioritize a) Urgent development of universal interoperability standards, and b) Protocols and design and empirical validation of multi-stakeholder incentive and governance models to overcome the identified fragmentation and participation barriers (Table 8).

4. Conclusions and future research directions

4.1. Conclusions

This study used bibliometric analysis to elucidate the significance of integrating digital technologies into A-FSCs, thereby transforming them

[7] Interplanetary File Storage System
[8] Proof of Supply Chain Stake
[9] Electronic Product Code Information Services

into SA-FSCs during the 2020s. The results revealed a substantial surge in published documents on SA-FSCs, with the number of publications from 2020 to mid-2024 being 1.5 times greater than the cumulative output over the preceding five decades. Furthermore, an annual growth rate of approximately 28 % was observed, underscoring the emergent and rapidly evolving nature of this research domain within the current decade. Notably, the high average document citation and the substantial level of international collaboration evident in this field suggest that research on optimizing A-FSCs through digital technologies poses universal challenges and requires a concerted global effort. Meanwhile, the pivotal roles and contributions of nations like China and India, which are among the world's largest producers of agricultural commodities, are considerable. However, these highly populous countries face complex logistical, distributional, and waste management challenges, necessitating a comprehensive approach to ensure food security for their vast, often underprivileged populations. Consequently, these nations exhibit a high volume of scientific output in this field, yet their studies tend to be more aligned with basic or foundational levels, addressing fundamental issues within their respective A-FSC systems. In contrast, developed nations such as Spain, Italy, the UK, and the US, having addressed the fundamental issues within their A-FSCs, are better positioned to conduct cutting-edge, multidisciplinary research at the forefront of knowledge. This assertion is corroborated by the high average document citation and the substantial international collaboration observed in their research outputs. Intriguingly, during the 2020s, journals published by MDPI have surpassed those of the Elsevier group in terms of the number of articles published in this domain. This trend can be attributed to MDPI's propensity to publish more articles related to foundational knowledge from less developed countries, owing to its relatively recent establishment and lower levels of stringency compared to the long-standing Elsevier group.

Co-word analysis employed to uncover prevailing themes and emerging trends in the realm of SA-FSCs. The findings revealed five central axes: food safety and food waste, A-FSC management and traceability, sustainable development in A-FSCs, digital technologies in A-FSCs, and innovation and technology adoption in A-FSCs. Notably, these axes exhibit intrinsic interconnectedness and interdependence in achieving optimal A-FSCs. For instance, sustainable development hinges on the collective progress of other axes, while sustainability underpins policies for effective management. Moreover, these axes exert synergistic effects, collectively driving substantial advancements in research and operations within this domain.

Further, co-citation analysis was used to explore the foundational and influential topics and concepts in the domain of SA-FSCs. Notably, the top 10 most cited references centered around the various dimensions of blockchain technology application across of A-FSCs. This finding highlights the growing significance and increasing prominence of traceability and blockchain technology as critical tools for optimizing SA-FSC management. Traceability, through its inherent functionalities, can facilitate the realization of diverse objectives, ranging from reducing food waste and ensuring food security to harnessing sustainability within A-FSCs. Simultaneously, blockchain technology, through its high security and wide applicability, can play a pivotal role in this context.

Further analysis revealed that foundational and influential themes within the field of SA-FSCs during the 2020s could be summarized into four central axes: sustainable A-FSC management, blockchain applications in A-FSCs, blockchain-based solutions for agri-food safety and traceability, and challenges and requirements of blockchain adoption in A-FSCs. The extensive application of blockchain technology and the high enthusiasm of researchers for this technology underscore its significance, applications, and substantial contribution towards achieving optimal management of A-FSCs compared to other digital technologies such as IoT, AI, Big Data, and Machine Learning.

While the proper application of these technologies alongside blockchain is crucial and can enhance A-FSC management, blockchain plays a more significant role. The findings suggest that traceability technologies like blockchain have a profound impact on optimal and sustainable A-FSC management but face various challenges and requirements, especially in SMEs and labor-intensive production stages, that should be taken into account.

Finally, this study conclude that SA-FSCs in the current decade exhibit a growth trend due to their unique functions enabling optimal and sustainable management of A-FSCs in research and operations. However, their proper application faces numerous complications, requirements, and challenges across different supply chain stages, agri-food systems, and geographical areas. Therefore, policymakers in this field should consider the axes introduced in this study in an integrated and interconnected manner, striving for appropriate adaptation of SA-FSCs across various sectors while adhering to the SDGs criteria.

4.2. Scientific contribution

The current study presents a significant and novel contribution to the literature on SA-FSCs through its rigorous, large-scale, and methodologically sophisticated bibliometric analysis. Its novelty is evident in several key aspects when compared to existing reviews. Firstly, its temporal specificity is a major advancement. By focusing exclusively on the highly dynamic period of 2020–2024 (Fig. 4), the study captures the most recent surge in research driven by accelerated digital adoption post-pandemic and heightened focus on supply chain resilience, a recency unmatched by broader reviews like Rejeb et al. [34] or Lezoche et al. [30]. Secondly, the methodological integration sets it apart. While many studies employ bibliometrics [21,23,24], this paper synergistically combines co-word analysis to identify emerging thematic axes with co-citation analysis to uncover foundational themes, providing a dual-layered understanding of the field's intellectual structure and dynamic frontiers simultaneously. This surpasses studies relying solely on performance analysis or basic keyword mapping. The synergistic application of co-word and co-citation analyses offers a comprehensive view of a research field's evolution, pinpointing emerging themes, influential works, and conceptual interconnections, thus guiding scholars in understanding past trends, current status, and potential future directions [38]. Thirdly, the scale and comprehensiveness are noteworthy. Analyzing 3334 articles provides a robust empirical foundation, larger than many comparable reviews [21,24,32]. Its holistic SA-FSC focus, avoiding fragmentation into specific technologies like blockchain [25,27] or sustainability dimensions [22,24], allows for synthesizing broader trends. Fourthly, the clarity of thematic synthesis is a distinct contribution. The identification of five coherent emerging axes and four foundational clusters provides a clearer conceptual map than the often more disparate clusters found in broader analyses [23,33]. Crucially, the co-citation analysis rigorously highlights the centrality of traceability, specifically blockchain, within the SA-FSC digital technology landscape, confirming and contextualizing trends noted in specialized blockchain reviews [25,26,39] within the wider SA-FSC evolution. Finally, its practical orientation enhances novelty. By explicitly deriving perspectives to assist policymakers and researchers in identifying prevalent and emerging trends for targeted contributions, it moves beyond mere description towards actionable insights, addressing a gap sometimes present in purely analytical bibliometric works. While building upon the foundation laid by previous bibliometric studies in agri-food digitalization, sustainability, and specific technologies, this paper's combination of recent temporal scope, advanced dual-method analysis, large-scale data, clear thematic synthesis, and practical focus establishes its significant novelty and value in mapping the rapidly evolving intellectual terrain of SA-FSCs.

4.3. Future research directions

In terms of future research, some areas that may be subject of further research are:

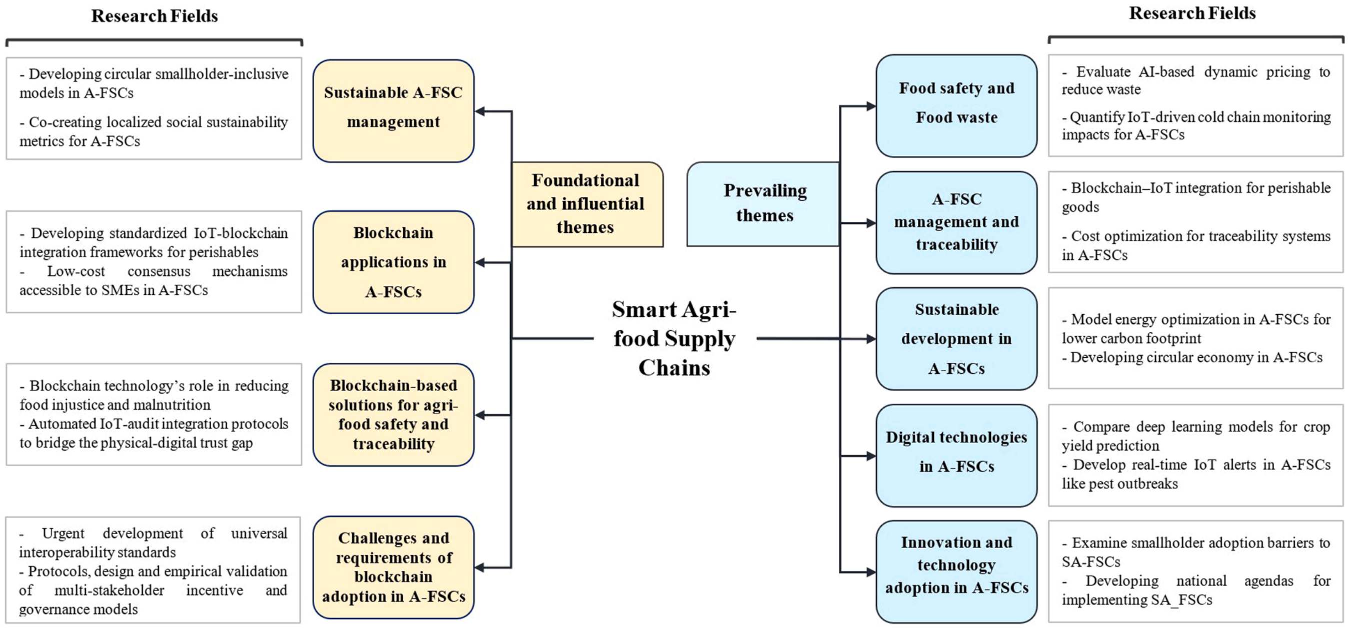

Fig. 9. Research agenda for optimizing research efforts in the field of SA-FSC.

a) Regional benefits of SA-FSCs: Recognizing the importance and impact of SA-FSCs on improving economic, social, and environmental conditions in the agri-food sector, there is a pressing need for more research on regional and national studies to explore the benefits and functions of these supply chains across different countries worldwide.
b) Adoption of SA-FSCs at regional scales: Given the challenges and requirements associated with implementing and adapting SA-FSCs in the agri-food sector of diverse regions, coupled with the unique social, infrastructural, economic, and environmental characteristics of these regions, there is a greater necessity for feasibility and adaptability studies focused on the application of SA-FSCs in various regions globally.
c) Principled integration of digital technologies in SA-FSCs: Considering the current limitations and challenges faced by digital technologies employed in SA-FSCs, particularly traceability tools (especially blockchain), further research is needed to integrate these technologies in a user-friendly manner, leveraging their complementary strengths to overcome individual shortcomings and enable faster and more sustainable development.
d) Developing SA-FSCs in labor-intensive forms: Recognizing that a significant portion of the world's population resides in underdeveloped countries, where economic, technological, cultural, and educational barriers may hinder the adoption of cutting-edge, expensive, and highly complex technologies, more studies are required to explore the optimal integration of labor-intensive activities with SA-FSCs.
e) Sustainability in SA-FSCs: With the rapid growth and increasing use of digital technologies in A-FSCs, all sustainability requirements should be considered to prevent unintended environmental degradation, cultural heritage loss, and local economic disruptions across various regions. Consequently, research in this field is crucial before implementing the SA-FSCs in different regions.

Finally, based on the findings of this study regarding prevailing themes and foundational and influential themes, a structured and concise research agenda was formulated to guide and enhance future studies on SA-FSCs. This agenda proposes two distinct research domains for each of the prevailing themes (identified through co-word clusters) and foundational and influential themes (identified through co-citation clusters), directing studies toward critical needs and optimizing research efforts in the field of SA-FSCs. The research agenda is illustrated in Fig. 9.

5. Limitations

Despite its substantial contributions, the study is not devoid of limitations. This study is intentionally based solely on the Scopus database. While combining multiple databases can offer advantages, the deliberate selection of the Scopus database allowed us to minimize potential discrepancies and duplications that may arise from merging different sources, while simultaneously providing access to a comprehensive range of literature relevant to the research topic. Nonetheless, we acknowledge the benefits of employing multiple databases and encourage future researchers to explore this approach to gain additional insights and knowledge. Furthermore, the analysis was specifically focused on English-language journal articles, excluding other document types such as conference papers, reviews, book chapters, books, conference reviews, notes, editorials, retracted materials, and erratum. This deliberate choice aimed to further enhance the validity and accuracy of the content by leveraging the systematic and rigorous peer-review processes associated with journal articles, while also mitigating potential content overlaps across different document formats. However, future researchers may consider incorporating other document types into their analyses. In this study, we employed keyword co-occurrence and co-citation analysis for network analysis, although other techniques, such as bibliographic coupling, could potentially yield interesting results as well. Additionally, it is important to acknowledge that the findings of this study may be subject to potential biases in the interpretation and classification of articles into distinct clusters and concepts. Despite efforts to ensure accuracy and comprehensiveness, it is possible that other researchers may classify and interpret the results differently, reflecting the inherent subjectivity in such analyses. Finally, it is crucial to recognize that the subject of study is rapidly evolving over time, necessitating regular and continuous monitoring of emerging prospects, trends, and new scientific developments within this domain. Consequently, future research endeavors should periodically reassess and update the findings to maintain relevance and capture the latest advancements in the field.

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Declaration of generative AI and AI-assisted technologies

During the preparation of this work the authors used Claude.ai in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Seyed Erfan Hosseini: Writing – original draft, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Ali Akbar Barati:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Ali Asadi:** Writing – review & editing, Validation, Project administration. **Ali Bozorgi-Amiri:** Writing – review & editing, Validation, Conceptualization. **Hossein Azadi:** Writing – review & editing, Validation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Appendix A1, Appendix A2, Appendix A3

Appendix A1
Top 10 most productive authors based on the number of published documents.

Authors	Affiliation	Total publications	H-index
Luthra, S.	All India Council for Technical Education (India)	16	64
Kumar, A.	London Metropolitan University (United Kingdom)	15	43
Mangla, S.K.	O.P. Jindal Global University (India)	15	65
Raut, R.D.	Indian Institute of Management Mumbai (India)	14	45
Kazancoglu, Y.	Yaşar Universitesi (Turkey)	13	35
Kamble, S.	EDHEC Business School (France)	12	40
Mor, R.S.	University of Northampton (United Kingdom)	11	17
Zhang, X.	Heilongjiang Bayi Agricultural University (China)	10	12
Defraeye, T.	Empa - Swiss Federal Laboratories for Materials Science and Technology (Switzerland)	9	44
Jagtap, S.	Cranfield University (United Kingdom)	9	20

Appendix A2
Top 10 most productive countries based on the total number of published documents.

Country	No. documents	Total citations	Average document citation	MCP ratio
China	508	7562	14/90	30.1 %
India	297	5247	17/70	27.9 %
United States	211	4390	20/80	27.5 %
Italy	179	3639	20/30	27.4 %
United Kingdom	154	3352	21/80	55.2 %
Brazil	91	696	7.60	29.7 %
Germany	85	1270	14.90	37.6 %
Australia	78	1342	17.20	46.2 %
Indonesia	67	421	6.30	17.9 %
Spain	59	1330	22.50	25.4 %

Appendix A3
Top 10 leading journals based on the total number of published documents.

Journals	Publisher	No. documents	Citations	Best rank	Impact Factor
Sustainability (Switzerland)	MDPI	191	2467	Q1	3.9
Journal Of Cleaner Production	Elsevier	88	2404	Q1	11.1
IEEE Access	IEEE	65	1416	Q1	3.9
Foods	MDPI	54	783	Q1	5.2
Nutrients	MDPI	49	669	Q1	5.9
International Journal of Environmental Research and Public Health	MDPI	48	613	Q2	3.3
Frontiers In Sustainable Food Systems	Frontiers	46	236	Q1	4.7
Agriculture (Switzerland)	MDPI	33	197	Q1	3.6
British Food Journal	Emerald	33	247	Q1	3.3
Energies	MDPI	30	231	Q1	3.2

Data availability

Data will be made available on request.

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