Food and Humanity 5 (2025) 100736

Contents lists available at ScienceDirect

Food and Humanity

journal homepage: www.editorialmanager.com/foohum/journal_overview.html

Smart food supply chain management: A bibliometric and systematic review

Mona Jabor Al-Thani, Majed Hadid *, Regina Padmanabhan, Laoucine Kerbache, Adel Elomri

Division of Engineering Management and Decision Sciences, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha, Qatar

ARTICLE INFO

Keywords:
Smart Food Supply Chain management
Food Security
Internet of Things
Artificial Intelligence
Systematic Review

ABSTRACT

The food supply chain (FSC) faces increasing pressure due to rising global demand, inefficiencies, food safety concerns, and sustainability challenges. The Internet of Things (IoT) offers significant potential for transforming supply chain management across key stages, production, processing, distribution, and retail. By integrating IoT technologies in supply chains, organizations can enable real-time monitoring, automation, and predictive analytics through interconnected devices such as sensors, Radio-Frequency Identification (RFID) tags, smart packaging, and automated systems. This study conducts a systematic review and bibliometric analysis of IoT-enabled FSCs, following PRISMA guidelines, to examine how IoT enhances food security, optimizes efficiency, and promotes sustainability while identifying key research trends, technological advancements, challenges, and opportunities. A search in scientific databases for the period 2018–2024 yielded 33 articles, which were analyzed to classify IoT applications, explore integration with blockchain and artificial intelligence (AI), and assess benefits and barriers. Content analysis of the reviewed literature identified key thematic clusters. These include IoT integration in supply chain management, advanced technologies for efficiency, traceability and security, food quality and safety, logistics optimization, and the role of Industry 4.0 in smart farming. Findings reveal that IoT improves traceability, cold chain management, quality control, and predictive analytics. Within farm environments, precision agriculture employs IoT sensors to monitor soil, crop health, and weather conditions, optimizing resource allocation. In distribution, IoT-enabled packaging and cold chain systems ensure food freshness by tracking temperature and humidity. At the retail level, smart shelves with weight sensors and tracking technology automate restocking, while IoT refrigerators monitor temperature and expiration dates, reducing waste. Despite these benefits, high costs, data privacy concerns, and interoperability issues hinder adoption. The bibliometric analysis highlights a growing focus on IoT-blockchain integration and gaps in cost-effective, user-friendly solutions. Strategies include open-source platforms, standardization, and improved interfaces. This study offers insights into advancing IoT adoption in FSC management.

1. Introduction

The global food supply chain (FSC) is under unprecedented pressure due to rapidly growing populations, increasing demand for safe and sustainable food, and rising concerns over resource scarcity and climate change (Lee, Zeng, & Luo, 2024). According to the United Nations, as reported in FAO, (2017)), in the future of food and agriculture, the global population is projected to reach 9.7 billion by 2050. This will necessitate a 70 % increase in food production to meet the demand for safe and nutritious food as per FAO, (2009)), global agriculture towards 2050. At the same time, food waste, supply chain inefficiencies, and food safety concerns continue to undermine global food security, contributing to economic losses and environmental degradation as reported in FAO (2022), the future of food and agriculture: drivers and triggers for transformation.

In this context, the Internet of Things (IoT) has emerged as a transformative force capable of revolutionizing the agri-FSC through real-time monitoring, predictive analytics, automation, and improved traceability (Dadi, Nikhil, Mor, Agarwal, & Arora, 2021). IoT technologies connect physical objects (such as sensors and devices) to digital systems, enabling seamless data collection, analysis, and sharing across the supply chain. These technological advancements offer critical

* Corresponding author.
E-mail address: mahadid@hbku.edu.qa (M. Hadid).

https://doi.org/10.1016/j.foohum.2025.100736
Received 29 December 2024; Received in revised form 27 July 2025; Accepted 28 July 2025
Available online 30 July 2025

opportunities for enhancing efficiency, reducing food waste, ensuring food safety, and supporting sustainable practices, making IoT a cornerstone for addressing contemporary and future food system challenges (Goyal, Kanyal, & Sharma, 2023).

Importantly, the integration of IoT in FSCs aligns with several United Nations Sustainable Development Goals (SDGs), underscoring the global significance of this topic. Specifically, IoT-enabled FSCs contribute to multiple critical goals. First, they support SDG 2 (Zero Hunger) by optimizing production and distribution processes, reducing food loss, and improving food security, thereby ensuring better access to safe and nutritious food for growing populations (Morales & Elkader, 2020). Furthermore, IoT fosters innovation and technological infrastructure in agriculture and logistics, contributing to the modernization of food systems in line with SDG 9 (Industry, Innovation, and Infrastructure). In addition, by enabling real-time monitoring and predictive analytics, IoT facilitates efficient resource management, waste reduction, and improved supply chain transparency, which align with SDG 12 (Responsible Consumption and Production) (Fatimah, Govindan, Murniningsih, & Setiawan, 2020). Finally, IoT technologies contribute to SDG 13 (Climate Action) by optimizing agricultural practices, minimizing food waste, and reducing greenhouse gas emissions associated with food production and distribution (Teh & Rana, 2023). Therefore, leveraging IoT in FSCs holds transformative potential to address global challenges related to food security, sustainability, and environmental impact.

Given the urgent need to transform traditional FSCs into resilient, transparent, and sustainable networks, IoT adoption offers a promising pathway. However, despite its potential, the implementation of IoT across food systems remains fragmented and uneven, particularly between developed and developing regions. Challenges such as high costs, technical infrastructure gaps, data security issues, and regulatory uncertainties continue to limit widespread IoT adoption, creating a critical need for comprehensive research and evaluation of current practices, trends, and barriers.

In recent years, there has been an explosive growth in the research and application of IoT technologies within FSCs. The surge in IoT-driven solutions reflects increasing global attention to challenges such as food safety, traceability, waste reduction, and supply chain optimization. An expanding body of research is now exploring how IoT, often coupled with blockchain, big data analytics, and artificial intelligence (AI), can revolutionize agri-food systems. The rapid proliferation of academic publications in this field underscores both the relevance and urgency of comprehensively mapping this evolving landscape. However, despite this growing body of knowledge, an integrative review that consolidates existing insights while identifying gaps remains limited.

Several notable reviews have addressed aspects of IoT applications in food systems, but they vary in scope, depth, and focus (Table 1). For instance, Ahmadzadeh, Ajmal, Ramanathan, & Duan (2023) provided a review of IoT and big data applications for food waste reduction, emphasizing smart supply chains and outlining technical models and frameworks. Ben-Daya, Hassini, Bahroun, & Banimfreg (2020) reviewed the role of IoT in FSC quality management, focusing largely on traceability and quality assurance but without fully covering the entire spectrum of supply chain stages and emerging technologies. Bhat, Huang, Sofi, & Sultan (2021) explored blockchain and IoT integration for agri-FSC management, focusing primarily on the interoperability and transparency challenges of blockchain but offering limited analysis on IoT adoption barriers or practical deployment strategies across diverse FSC contexts. Furthermore, Araújo, Peres, Barata, Lidon, & Ramalho (2021) discussed Agriculture 4.0, encompassing IoT and AI as part of broader technological transformations in agriculture, though their focus extended beyond supply chain-specific issues. Reviews such as Ferhat Taleb, Benalia, & Sadoun (2023) analyzed IoT combined with evolutionary algorithms for precise irrigation, but this work is limited to agricultural production and does not encompass the post-harvest, distribution, and retail dimensions of the FSC. Lastly, Mehannaoui, Mouss, & Aksa (2023) reviewed IoT-based traceability systems, addressing technical architectures but not elaborating on their integration with broader FSC management and sustainability goals.

This review seeks to address the identified review gaps by offering an analytical and integrative examination of IoT implementation within FSCs. It explores recent technological advancements and IoT system architectures applicable to food supply networks, examines the diverse applications of IoT across different key stages and discusses the main obstacles hindering IoT adoption, whether technical, economic, or regulatory. Moreover, it identifies practical solutions and future research opportunities to enhance the role of IoT in promoting more sustainable, efficient, and secure FSCs.

This paper is organized into five main sections. Section 2 explains the methodology and data collection process, detailing the bibliometric analysis conducted through the scientific databases along with the applied search strategy and the inclusion and exclusion criteria used to select relevant studies. Section 3 begins by providing a classification of the reviewed studies based on sector, technology, and methodology, followed by a comprehensive content analysis of IoT applications in FSCs. This includes their integration with emerging technologies such as blockchain and AI, and examines IoT applications across various stages of the supply chain, from production and processing to distribution and retail. Section 4 offers a discussion of the main insights drawn from the analysis, focusing on the opportunities and benefits of IoT, identifying key challenges and barriers to its adoption, and presenting practical recommendations for future research, and managerial insights. Finally, Section 5 concludes the paper.

Table 1
Comparison of previous review papers.

Reference	Methodology	Domain	Subdomain
Ben-Daya et al. (2020)	Bibliometric analysis and narrative review	FSC	Quality management, traceability, and safety
Bhat et al. (2021)	Narrative review	Agri-FSC	Blockchain and IoT interoperability
Araújo et al. (2021)	Systematic review with text mining	Agriculture (general)	IoT, AI, robotics, and data-driven agriculture
Ferhat Taleb et al. (2023)	Narrative review	Precision agriculture	IoT-based smart irrigation
Mehannaoui et al. (2023)	Narrative review	Food Traceability	IoT-based food traceability and tracking
Ahmadzadeh et al. (2023)	Narrative review	FSC	Food waste management
This Review	Systematic review and bibliometric analysis	FSC	IoT-enabled supply chain management

2. Methodology

According to Mayring & Fenzl (2019), content analysis and research methodology can be systematically structured into four key phases: gathering relevant materials, conducting a descriptive review, defining categories, and analyzing the material. This study adopts these phases to clarify and detail the methodological approach implemented. Additionally, the research process was guided by the 2020 PRISMA guidelines and checklist for systematic reviews and meta-analyses (Page et al., 2021).

2.1. Material collection

This literature review adopted a comprehensive search strategy to identify pertinent studies from electronic sources, primarily utilizing Scopus, Google Scholar, and ResearchGate databases. No time limitations were imposed, enabling a broad exploration of research across various periods. A systematic approach was applied to determine appropriate search terms. Initially, a pilot search was performed using preliminary keywords such as IoT, digital FSCs, food security, optimization, simulations, and decision-making tools. Based on the review of titles and abstracts from the initial search results, additional relevant terms were identified, and the keyword set was progressively refined to ensure broader coverage. The final search query is presented in Table 2, while the inclusion criteria guiding article selection are detailed in Table 3.

As show in Fig. 1, The initial search yielded 1497 records. To refine the results, publications were filtered to include only articles published between 2018 and 2024 and written in English, reducing the number to 1278 records.

During the screening phase, the titles and abstracts of these articles were reviewed to determine their relevance. Articles that were unrelated to supply chains, derived from non-data-driven fields, or belonging to irrelevant research domains were excluded. This screening process resulted in 94 articles selected for further assessment.

A full-text review of 94 articles was conducted to assess eligibility based on inclusion criteria. Several articles were excluded at this stage, including purely technical papers lacking any supply chain context, non-original review papers, and economic analyses that did not focus on supply chain operations.

Finally, a total of 33 articles were selected for inclusion in the study. These articles provided valuable insights and contributions to the integration of IoT, predictive analytics, simulation models, and decision-support tools within the context of digital FSCs.

2.2. Descriptive analysis

Fig. 2 presents a tree map of the most common keywords leading to a comprehensive keyword analysis of the reviewed literature related to smart FSCs, highlighting the main themes and emerging research directions in this domain. Notably, "decision support systems" and "internet of things" emerge as the most prominent keywords, reflecting the growing focus on leveraging advanced technologies to enhance decision-making and real-time monitoring in FSC operations. Keywords such as "decision making," "agriculture," "artificial intelligence," and "machine learning" further emphasize the integration of intelligent tools to optimize agricultural practices and supply chain processes. Fig. 3 shows Co-word network analysis to visualize how keywords co-occur within the reviewed articles to reveal underlying themes, relationships, and research trends. The centrality of 'decision support systems' in Fig. 3 reflects the field's focus on data-driven optimization.

The frequent appearance of "climate change" and "water quality" highlights the increasing concern for sustainability and environmental factors influencing the supply chain. Additionally, terms like "forecasting," "data analytics," and "automation" suggest a trend towards predictive and data-driven approaches for improving supply chain efficiency. Interestingly, the presence of keywords such as "quality control," "food supply," and "crops" underscores the critical importance of ensuring food quality and security within smart supply chain frameworks.

Overall, this analysis reveals that the research community is actively exploring the intersection of digital technologies, sustainable agriculture, and supply chain optimization to address modern challenges in food systems.

Fig. 3 also highlights strong interconnections between technological methods and application domains, as seen in the links connecting "precision agriculture," "agricultural robotics," and "quality control" to the core technological nodes. This signifies that smart methodologies are not only theoretical but are being actively implemented in real agricultural and food production settings. The linkage between "climate change," "water quality," and "sustainable agriculture" also suggests that methodological approaches are increasingly designed to incorporate environmental and sustainability considerations, pointing to a growing trend toward resilient and eco-friendly supply chains.

Interestingly, peripheral nodes such as "human" and "industry 4.0" are connected through other nodes, suggesting emerging but less explored intersections that may represent future directions for integrating human-centered design, policy considerations, and industrial innovation into smart FSCs. Collectively, this network visualization underscores that the field is characterized by a convergence of data-driven, AI-based methodologies intricately connected to technological, environmental, and practical agricultural domains, highlighting a multidisciplinary and interconnected research approach.

Fig. 4 illustrates the temporal distribution of the reviewed papers on smart FSCs, spanning from 2014 to 2024. The figure clearly demonstrates a noticeable surge in publications in the past three years, with a peak of 11 articles in 2023, followed by 8 and 7 papers in 2022 and 2024, respectively. This upward trend reflects the growing academic and industrial interest in applying smart technologies to FSCs, likely driven by increasing global challenges such as food security, sustainability, and supply chain disruptions.

Interestingly, earlier years, such as 2014, 2017, and 2018, show only one publication each, indicating that the research field was relatively nascent during that period. A moderate increase appears in 2020 with 4 articles, possibly linked to heightened attention to supply chain resilience during the COVID-19 pandemic. However, no publications were identified for 2015, 2016, 2019, and 2021, highlighting periods of limited focus on this topic.

Overall, this temporal analysis suggests that research on smart FSCs is an emerging and rapidly evolving area, particularly gaining momentum in the last few years as technological advancements and global needs align to drive innovation in this field.

2.3. Category selection

Table 4 presents the classification and content analysis framework of this review, highlighting the main analytical themes and specific classifications. These categories have been developed based on a thorough examination of the selected papers, with the goal of creating an appropriate and comprehensive classification system for all the studies analyzed.

2.4. Material evaluation

The study ensured strong validity by conducting thorough validation tests, applying both deductive and inductive approaches simultaneously. To minimize errors during content extraction and to evaluate different elements of the analysis, structured tables were employed. Moreover, the content analysis was carried out through an iterative process that included gathering feedback, refining and expanding the extraction tables, and revisiting the analysis of the selected papers.

3. Content analysis

This section presents a detailed analysis of the reviewed literature focusing on the integration of IoT technologies in FSCs. The analysis explores how IoT is employed across different stages of the supply chain, the role of complementary technologies such as blockchain and AI, and

Table 2
Search query.

(IoT OR "Internet of Things" OR "machine-to-machine") AND (Food) AND ((supply chain) OR ("data-driven optimization" OR "supply chain optimization" OR "logistics optimization" OR "predictive analytics" OR simulations OR "digital twins" OR "modeling" OR "decision-making tools" OR "decision support systems" OR "interactive dashboards")

Table 3
Filtering criteria.

1. Query search terms must exist in the publication title, abstract, or keywords
2. Only retain publications that satisfy the following conditions:
o Language: English
o Time: 2018–2024

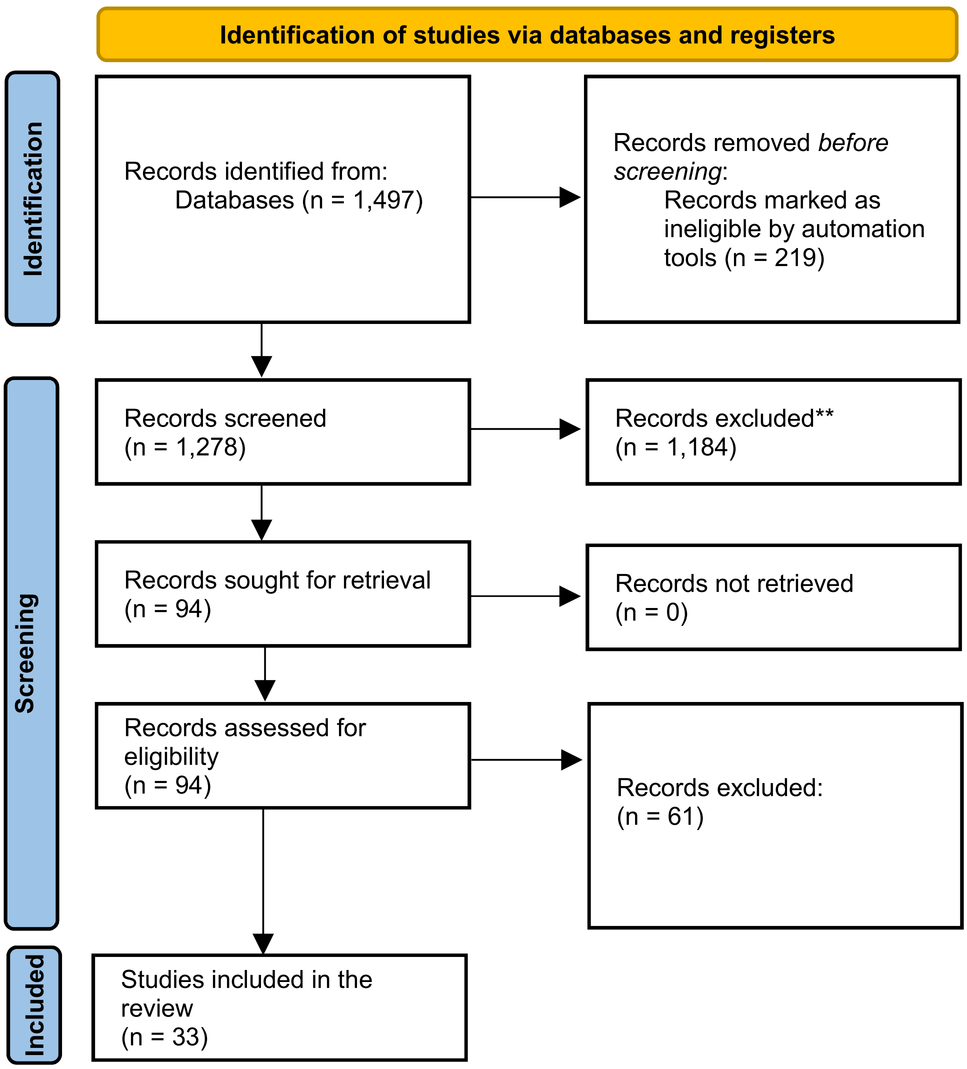

Fig. 1. Flow Chart of the Study Selection Process Based on Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Page et al., 2021).

the benefits and advancements in improving food security, efficiency, and sustainability.

Table 5 provides a classification of the reviewed studies based on their focus areas, methodologies, and technologies used. The table highlights the diversity of approaches in applying IoT within FSCs, including its integration with blockchain, AI, and big data analytics, as well as its role in addressing challenges such as traceability, food quality, security, and waste reduction.

Analyzing the studies summarized in Table 5 reveals several key trends in the integration of IoT technologies in FSCs. First, real-time monitoring emerges as a critical application, with IoT sensors and devices enabling continuous tracking and monitoring of products from production to transportation stages (Sarkar, Akshatha, Saurabh, Samanvitha, & Sarwar, 2022). Second, blockchain integration is a recurring theme, where studies like (Addou, El Ghoumari, Achkdir, & Azzouazi, 2023) emphasize the combined role of IoT and blockchain in improving traceability, ensuring transparency, and addressing issues related to food fraud. Third, urban food supply optimization is gaining attention, as shown in the work of Girirajan et al. (2024), which demonstrates how IoT-based systems contribute to urban food distribution management through dynamic vehicle routing and real-time logistics coordination. Moreover, precision agriculture represents another vital area where IoT supports efficient resource management and sustainable agricultural practices, as highlighted by Gürdil et al. (2024). Finally, sustainability models are being developed to leverage IoT for reducing food loss and waste, with examples such as İzmirli et al. (2020) demonstrating the environmental benefits of IoT-enabled solutions.

Collectively, these findings suggest that IoT's transformative potential lies in its ability to connect with complementary technologies such as blockchain and AI to optimize supply chain operations, enhance food security, and promote sustainability.

The following subsections provide an in-depth discussion of these

Fig. 2. Tree Map of the most common keywords.

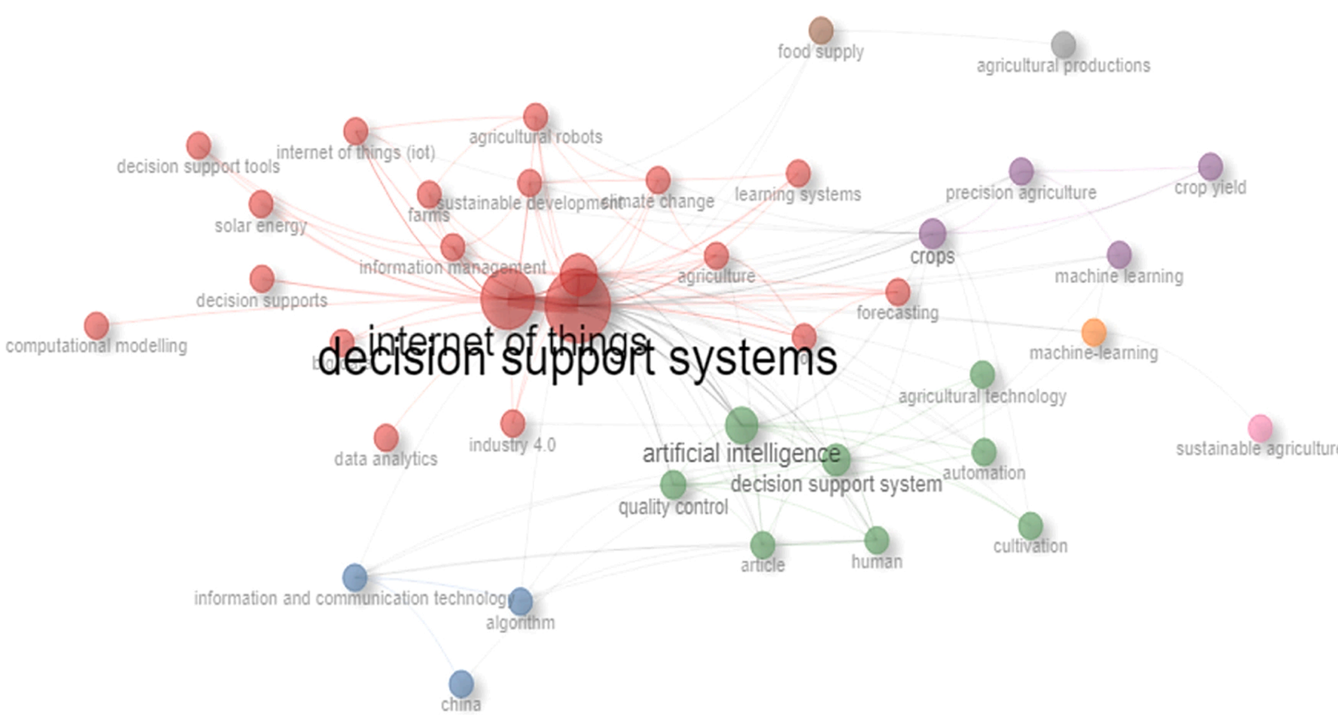

Fig. 3. Co-word Net.

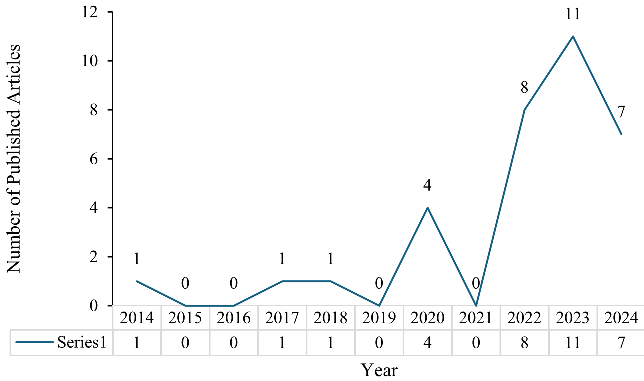

Fig. 4. Temporal distribution of reviewed articles.

Table 4
Overview of the categorization system content analysis framework.

Categories	Aspects
1) Sector	1) IoT Integration in FSCs and Management
a) Agri-Food	2) Advanced Technologies Enhancing Supply Chain Efficiency and Decision-Making
b) Supply Chain	
c) Technology	3) IoT and Emerging Technologies for Traceability, Transparency, and Security
2) Technology	
a) IoT	4) IoT's Role in Food Quality, Safety, and Monitoring
b) Blockchain	5) IoT-Driven Logistics, Inventory, and Dynamic Supply Chain Optimization
c) AI/ML	
d) Digital Technologies	6) Industry 4.0 and Smart Farming for Agri-FSCs
3) Methodology	
a) Empirical	
b) Theoretical	
c) Simulation	

trends and technologies, exploring the integration of IoT in FSCs, the methods and tools used, and the specific benefits achieved in terms of efficiency, safety, and transparency.

3.1. IoT integration in FSCs and management

3.1.1. IoT in FSCs

The IoT is rapidly transforming various sectors from optimizing urban living in smart cities (Zhang, Huang, Zhu, & Qiu, 2013), to revolutionizing agricultural practices (Dinesh Dattatraya Rankhamb et al. 2024). By embedding sensors in physical objects and leveraging the internet, cloud computing, and AI, the IoT enables efficient city management and enhances resource utilization in agriculture. This includes precise monitoring of soil conditions and water usage, which are crucial for sustainable farming and addressing food security concerns (Mukherjee, Dutta, & Bandyopadhyay, 2021). Advancements such as Narrowband IoT (NB-IoT) are improving communication infrastructure by supporting massive device connectivity with minimal energy consumption (Mohammed & Chopra, 2023). Adoption of IoT in FSC facilitated real-time monitoring, predictive analytics, and automated decision-making. For example, sensors monitor critical parameters such as temperature, humidity, and contamination risks, enabling stakeholders to prevent food spoilage (Hassoun et al., 2023). In agriculture, IoT devices such as soil sensors provide real-time data on soil moisture and nutrient levels, allowing farmers to make data-driven decisions that optimize resource allocation and increase yields (Mukherjee et al., 2021). Moreover, the IoT has applications in FSC management, offering improved efficiency and transparency (Dutta & Mitra, n.d.; Moudoud et al., 2019; Mukherjee et al., 2021).

However, the widespread adoption of the IoT presents challenges such as high costs and inadequate infrastructure. Data privacy and security are paramount concerns, along with the need for robust infrastructure to handle massive data influx (Dutta & Mitra, n.d.; Moudoud et al., 2019). Addressing these barriers requires developing cost-effective solutions tailored to different stakeholders in the supply chain (Raza et al., 2023). Furthermore, ensuring interoperability between IoT devices and systems remains critical for enabling large-scale adoption.

Despite challenges related to security, privacy, and infrastructure, the opportunities presented by IoT are vast. In agriculture, IoT enables smart farming practices that optimize crop production, minimize waste, and enhance sustainability through precision irrigation, real-time monitoring of soil and crop health, automated pest and disease detection, and efficient resource management (Dinesh Dattatraya Rankhamb et al. 2024). These technologies empower farmers to make data-driven decisions, reduce excessive use of water and fertilizers, and improve overall productivity while minimizing environmental impact. Beyond agriculture, IoT's transformative potential extends to urban management and supply chain operations, driving efficiency and sustainability across various sectors. By addressing these challenges through innovative solutions and policies, IoT can continue to revolutionize industries and contribute to a more sustainable future (Dinesh Dattatraya Rankhamb et al. 2024).

Supply chain management is evolving rapidly in response to the complexities of modern commerce and increasing consumer expectations. Research has highlighted the critical need for efficiency, cost-effectiveness, and social responsibility in intricate networks (Huang & Fang, 2024). This necessitates a focus on technological integration, particularly through tools such as blockchain, to enhance traceability and transparency, in sectors such as the agri-food industry where provenance is paramount (Kale, Apte, Raut, Dorage, & Bhadkumbhe, 2019).

IoT applications enhance supply chain efficiency by improving traceability and visibility. For instance, blockchain-integrated IoT systems create tamper-proof records of food production and distribution, ensuring transparency and accountability (Addou et al., 2023). These systems also enable real-time tracking, allowing stakeholders to respond proactively to disruptions and minimize waste (Girirajan et al., 2024).

Nevertheless, challenges such as regulatory compliance, scalability, and cybersecurity need to be addressed to maximize IoT's potential. Recent studies emphasize the importance of standardized frameworks to ensure consistent data exchange and governance across supply chain networks (Fang et al., 2023). Successful adoption of these technologies requires standardized data models and adaptable legal frameworks (Shermin Voshmgir & Rammel, 2019). Thus, the two key challenges are related to policy and technology. Lack of standardized legal frameworks for blockchain implementation across supply chains is one challenge, as varying regulations across regions hinder easy adoption and interoperability. Absence of standardized and interoperable data models is a technology challenge, during integration of blockchain and other tools across diverse supply chain systems.

Environmental sustainability is another key focus driven by growing concerns about climate change and resource depletion. Companies integrate sustainable practices into their strategic planning, recognize long-term cost benefits, and positively impact brand reputation (Huang & Fang, 2024). This shift towards sustainability aligns with increasing consumer demand for ethical and environmentally responsible products.

Furthermore, transparency is no longer optional but necessary. Driven by consumer awareness and legislation such as the California Transparency in Supply Chains Act, companies are under pressure to provide clear insights into their supply chain operations (Shermin Voshmgir & Rammel, 2019). This enables consumers to make informed purchasing decisions and holds companies accountable for ethical sourcing and labor practices. Many companies have responded by adopting blockchain technology for end-to-end traceability, using IoT-enabled tracking systems to monitor production processes, and publishing sustainability reports to disclose their sourcing practices. In the FSC, these legislative pressures have accelerated the adoption of IoT

Table 5
Key contributions of reviewed studies in IoT applications for FSC.

Researchers	Sector			Technology				Methodology			Key Finding	Key Contribution
	Agri-Food	Supply Chain	Technology	IoT	Blockchain	AI/ML	Digital Tech	Empirical	Theoretical	Simulation		
(Toromade et al., 2024)	●			●				●			Real-time monitoring enhances traceability	Enhances inventory management, transparency
(Rahman, Zulkifli, Zainuri, & Anwar, 2024)	●							●			E-commerce hub boosts accessibility	Improves accessibility and affordability
(Gurkan A. K, Benny, Demirel, & Cevher, 2024)	●			●			●	●			IoT optimizes input usage	Increases crop yields
(Duan, Onyeaka, & Pang, 2024)	●				●			●			Secure transaction records	Improves safety
(Hanis & Fernando, 2024)		●		●				●			Efficient planning reduces waste	Improves inventory management
(Girirajan, Naick, Al-Jawahry, Revanasiddappa, & Rana Veer Samara Sihman Bharattej, 2024)	●			●				●			IoT model optimizes smart cities	Enhances efficiency
(Bhatlawande, Ghatge, Shinde, Anushree, & Patil, 2024)		●		●					●		IoT-based models for smart cities	Promotes sustainable urban food systems
(Wang et al., 2023)			●				●		●		Supports predictive analytics via virtual environments	Supports collaborative planning
(Hassoun et al., 2023)	●			●				●			Smart sensors ensure quality	Enhances quality control
(Wan Mohamad & Rakiman, 2023)	●			●					●		Industry 4.0 enhances supply chain	Promotes smart farming
(Shardeo, Patil, Dwivedi, & Madaan, 2023)	●				●			●			Blockchain enhances security and trust	Enhances security through blockchain integration
(Addou et al., 2023)	●			●	●			●			Blockchain-IoT model boosts transparency	Provides real-time data
(Singh & Raza, 2023)	●			●	●				●		Combined IoT-blockchain ensures safety	Regulates inventory systems
(Raza, Haq, & Muneeb, 2023)	●			●	●				●		Smart contracts automate transactions	Automates processes and secures transactions
(Singh, Khan, Dsilva, & Centobelli, 2023)		●		●	●						Research highlights blockchain complexities	Identifies key challenges in integration
(Kim, Ng, Sahni, Samian, & Seah, 2023)			●	●	●	●			●		Blockchain ensures IoT data integrity	Provides consumer insights and reduces waste
(Fang, Liu, Xiao, & Park, 2023)		●		●	●			●			Blockchain and IoT enhance traceability and safety	Improves supply chain security
(Adebunmi Okechukwu et al., 2023)	●			●	●				●		IoT-blockchain enhances cybersecurity	Improves data protection
(Bisht et al., 2022)			●					●			Real-time data boosts efficiency	Improves financial management processes
(Singh et al., 2022)			●		●				●		Blockchain enhances transparency	Promotes sustainable practices
(Jagtap, Rahimifard, & Duong, 2022)	●			●				●			IoT sensors monitor energy use	Improves operational efficiency
(Botín-Sanabria et al., 2022)			●				●		●		Virtual simulation aids optimization	Enhances resource allocation
(Sarkar et al., 2022)		●		●				●			IoT ensures perishable item conservation	Ensures cold chain integrity
(Quy et al., 2022)	●			●	●				●		IoT boosts productivity and safety	Enhances operational efficiency
(Gaudio, Chakraborty, & Curcio, 2022)	●			●				●			Wireless sensors monitor crop growth	Promotes sustainable farming
(Hellani, Sliman, Samhat, & Exposito, 2020)		●			●			●			Highlights scalability issues	Identifies barriers

(*continued on next page*)

Table 5 (*continued*)

Researchers	Sector			Technology				Methodology			Key Finding	Key Contribution
	Agri-Food	Supply Chain	Technology	IoT	Blockchain	AI/ML	Digital Tech	Empirical	Theoretical	Simulation		
(Casino et al., 2020)	●			●	●			●			Blockchain records ensure traceability	Provides secure provenance
(İzmirli, Ekren, & Kumar, 2020)			●				●			●	Digitalized food supply model reduces waste	Minimizes food waste
(Khan, Byun, & Park, 2020)			●	●	●	●	●		●		IoT optimizes large datasets	Enhances data visibility and provenance
(Subashini & Hemavati, 2022)	●			●		●		●			IoT and Big Data boost efficiency	Improves operational efficiency
(Britchenko, Cherniavska, & Cherniavskyi, 2018)		●			●			●			Flexible blockchain logistics	Enhances logistics efficiency
(Luque, Peralta, de las Heras, & Córdoba, 2017)	●							●			Industry 4.0 enhances competitiveness	Improves efficiency
(Nechifor et al., 2014)		●		●		●		●			Smart transportation improves monitoring	Supports logistics monitoring

and transparency measures. IoT sensors and RFID tags are increasingly used to track food products from farm to table, ensuring compliance with safety regulations and ethical sourcing requirements. For instance, Walmart and IBM's Food Trust blockchain initiative enables real-time tracking of food shipments, reducing fraud and contamination risks. Similarly, regulatory frameworks like the FDA's Food Safety Modernization Act (FSMA) mandates IoT-based traceability for high-risk foods to prevent foodborne illnesses, encouraging companies to integrate IoT solutions for improved monitoring and reporting (Duan, Onyeaka, Pang, & Meng, 2024). These advancements not only help businesses meet legal requirements but also enhance operational efficiency, reduce waste, and strengthen consumer trust in FSCs.

Achieving efficiency is of paramount importance in supply chain management, particularly in the food industry, where timing and resource utilization are critical. The integration of the IoT stands to revolutionize traditional practices by fostering real-time data collection and analysis. Implementing IoT-enabled sensors and smart meters, as evidenced in a beverage factory case study, allows businesses to monitor their energy consumption accurately, thereby facilitating informed operational decisions and leading to substantial cost savings (Jagtap et al., 2022).

Moreover, this technological advancement aligns with the broader Industry 4.0 framework, which emphasizes interconnected processes and customizable manufacturing practices. By adopting these innovative solutions, the Andalusian food industry, for example, can enhance its competitiveness and sustainability while responding to the growing demands of consumers for transparency and efficiency (Luque et al., 2017). Collectively, these advancements foster a more resilient and responsive supply chain, crucial for addressing both economic and environmental challenges.

Research methodologies in IoT are diverse, encompassing data collection through sensor deployment, analysis for improved efficiency, and integration of advanced technologies like AI and blockchain (Dattatraya Rankhamb et al. 2024; Mukherjee et al., 2021; Zhang et al., 2013). These methodologies aim to address challenges and unlock the transformative potential of IoT across various domains, paving the way for sustainable and innovative solutions.

To effectively address these multifaceted challenges, researchers have employed diverse methodologies. Mixed integer programming models help optimize network layouts and coordination strategies, (Huang & Fang, 2024) whereas proximity optimization methods focus on efficient transportation and warehousing(Huang & Fang, 2024). Blockchain technology enables the creation of decentralized systems for enhanced traceability (Kale et al., 2019), and environmental impact assessments guide sustainable supply chain management practices (Huang & Fang, 2024).

3.1.2. IoT and food security

IoT significantly contributes to food security by reducing waste, improving supply chain efficiency, and enhancing food safety. For example, IoT-enabled cold chain systems use sensors to monitor perishable goods during storage and transportation, ensuring optimal conditions and minimizing spoilage (Sarkar et al., 2022). Additionally, predictive analytics powered by IoT devices help forecast demand, preventing overproduction and reducing waste (Rahman et al., 2024).

However, food fraud and supply chain opacity remain critical issues. Integrating blockchain with IoT has shown promise in addressing these concerns by providing secure, traceable records of food origin and handling (Duan, Onyeaka, Pang, et al., 2024).

The integration of the IoT in the FSC represents a transformative shift that is crucial for enhancing food security. By utilizing a network of connected devices, IoT facilitates real-time monitoring of environmental conditions, such as temperature and humidity, during production, transportation, and storage. This capability is vital for reducing spoilage and ensuring food quality, ultimately contributing to reliable food supply. As outlined in Toromade et al. (2024), a transparent and traceable food network is essential to addressing risks associated with food safety and fraud. Consequently, IoT has emerged as a critical player in fortifying food security in an increasingly complex global landscape.

Technologies like IoT and blockchain not only streamline operations but also influence consumer trust, worker roles, policy decisions, and economic inclusivity. Hence, beyond logistics, the socioeconomic impact of these tools extends to sectors such as marketing and education while addressing critical issues of trust and privacy that accompany digital transformation. In marketing, AI-driven decision-making tools and big data analytics enable companies to analyze consumer behavior and optimize supply chain operations, ensuring that food products reach the right markets efficiently. Predictive analytics, for instance, help retailers like Tesco and Amazon Fresh manage inventory based on demand forecasts, reducing food waste and improving cost efficiency. In education, IoT-driven platforms enhance agricultural training and resource management by providing farmers and policymakers with real-time insights. Platforms such as Digital Green use interactive videos and AI-driven advisory services to educate smallholder farmers on best agricultural practices, improving productivity and sustainability. Additionally, in addressing trust and privacy concerns, blockchain-based decision-making frameworks enhance transparency by allowing stakeholders to verify the authenticity and ethical sourcing of food products. These technologies not only optimize logistics but also contribute to food security by ensuring consistent access to quality food, reducing waste, and supporting transparent supply chains that foster trust among consumers.

Beyond these direct applications, the integration of interactive decision-making tools strengthens resilience in FSCs, enabling rapid responses to disruptions such as climate change impacts and global health crises. As digital transformation accelerates, leveraging these technologies will become increasingly critical in ensuring equitable food distribution, enhancing consumer confidence, and promoting sustainable economic growth. Thus, deploying interactive decision-making tools is not merely an operational enhancement but a strategic necessity for building a more adaptive, secure, and efficient global food system.

3.1.3. Role of predictive analytics in enhancing supply chain efficiency

Leveraging predictive analytics significantly enhances supply chain efficiency, particularly in the food security context. By analyzing historical data and identifying patterns, predictive models can forecast demand, optimize inventory levels, and minimize waste, which are critical in managing perishable goods. For instance, incorporating big data and IoT can provide real-time insights into supply chain dynamics, allowing stakeholders to make informed decisions swiftly. This aligns with the findings of previous studies indicating the importance of real-time data in financial management processes (Bisht et al., 2022), and that the integration of predictive analytics with technologies such as AI facilitate advanced planning and rapid response to unexpected disruptions in supply chains. As the energy sector adopts digital solutions for sustainability, similar innovations, such as blockchain, can enhance transparency and traceability and significantly bolster efficiency in FSCs (Wang et al., 2023). Such advancements ultimately lead to improved food security through optimized data-driven practices.

3.1.4. Data-driven food security and interactive decision-making

The key findings and developments in the research topic of strengthening food security through data-driven optimization simulations and interactive decision-making tools primarily revolve around the integration of IoT and blockchain technologies in agriculture and FSCs. These technologies are being used to enhance operational efficiency, productivity, and food safety while also addressing the challenges posed by a growing global population and diminishing natural resources (Quy et al., 2022).

IoT technology has been applied in smart agriculture to improve various aspects of the agri-food value chain including food safety, quality, and traceability (Wan Mohamad & Rakiman, 2023). These include the use of sensors and wireless communication technologies to monitor crop growth and to ensure sustainable farm production (Kim et al., 2023). In addition, blockchain technology is used to create tamper-proof systems for real-time data acquisition, monitoring, and storage, which enhances the transparency and security of the FSC (Addou et al., 2023).

Furthermore, IoT and blockchain are being combined to develop smart agricultural systems that minimize human involvement in data collection, recording, and verification, thus ensuring that all participants in the agricultural FSC have equal opportunities (Kumar & Dwivedi, 2023a). These technologies also support the implementation of smart contracts and IoT networks to gather multiple data points about food status, which aids in decision-making processes within businesses (Addou et al., 2023).

In urban settings, IoT technology aids in the real-time monitoring, analysis, and management of the food business, ensuring food quality, and optimizing supply chain networks (Girirajan et al., 2024). The use of advanced analytics and machine learning models further supports these efforts by providing insights into consumer consumption patterns, dietary gaps, and food waste management (Suciu et al., 2021).

Through data-driven optimization simulations and interactive decision-making tools, food security has focused on integrating IoT and blockchain technologies to enhance agricultural productivity and supply chain management. The IoT is being extensively applied to smart agriculture, enabling real-time monitoring, analysis, and management of agricultural processes (Wan Mohamad & Rakiman, 2023). These include the use of modern sensors and wireless communication technologies to improve farming efficiency and productivity.

Blockchain technology is employed to ensure food safety and traceability within the supply chain. It provides a secure and transparent method for tracking food quality and safety by digitally monitoring the processes and data of the material resources (Kim et al., 2023). Innovative models have been proposed to address the challenges of the urban food supply in smart cities. For instance, an IoT-based Dynamical Food Chain of Supply using Dynamic Vehicle Routing and Fire Hawk Optimization has been suggested to improve the effectiveness and precision of the supply chain network while ensuring food quality (Girirajan et al., 2024).

Furthermore, integrating IoT and blockchain transforms traditional agriculture into smart farming by minimizing human involvement in data collection, recording, and verification, thus providing a more efficient and secure agricultural FSC (Kumar & Dwivedi, 2023b).

Strengthening food security through data-driven optimization simulations and interactive decision-making tools involves integrating advanced technologies like IoT and blockchain, to address challenges such as declining natural resources, unpredictable environmental conditions, and complex global FSCs (Fang et al., 2023).

One key opportunity lies in smart agriculture integration, utilizing IoT and big data to transition to smart agriculture, improving operational efficiency and productivity by integrating technologies such as wireless sensor networks and cloud computing (Quy et al., 2022). Food traceability and safety can be enhanced by implementing blockchain and IoT to monitor food quality and safety by digitally tracking data and material resource processes, thereby ensuring supply chain reliability (Addou et al., 2023; Fang et al., 2023).

Waste reduction and nutritional accuracy can be achieved by harnessing technologies such as computer vision and deep learning to analyze food waste and improve nutritional accuracy, leading to economic efficiency and better health outcomes (Vodă, Tudor, Chiţu, Dovleac, & Brătucu, 2021). Enhanced decision-making can be achieved by leveraging machine learning and smart contracts within IoT networks to improve decision-making processes in the FSC, ensuring transparency, and reducing human error in data collection and verification (Addou et al., 2023). Sustainable urban food systems can be developed by creating IoT-based dynamic FSC models for smart cities, improving food quality management and contamination detection, thereby enhancing the effectiveness of urban food systems (Girirajan et al., 2024).

As the complexities of FSCs intensify, the integration of interactive decision-making tools becomes indispensable for optimizing operations and enhancing food security. These tools leverage real-time data to empower stakeholders to make informed decisions and address challenges, such as waste reduction and efficient resource allocation. For instance, metaverse, an emerging digital environment, illustrates how advanced technologies such as augmented and virtual reality can facilitate collaborative planning and predictive analytics within food systems. By fostering immersive experiences, these platforms allow users to visualize and simulate various scenarios, aiding in identifying optimal pathways for action.

Furthermore, researchers emphasize that these tools have far-reaching socioeconomic implications beyond logistics, shaping industries like marketing and education while tackling key challenges related to trust and privacy in the digital age. Consequently, implementing interactive decision-making tools has become a vital strategy for enhancing food security in a rapidly evolving global environment.

3.1.5. Impact of real-time data visualization on stakeholder collaboration

In the realm of IoT-enabled smart FSCs, real-time data visualization significantly enhances stakeholder collaboration by providing a unified platform for information sharing and analysis. Stakeholders, from farmers to distributors, can access dynamic visual representations of data, facilitating timely decision making and responsiveness to changing conditions. This transparency fosters trust and encourages collaboration as each party can see how its actions affect the entire supply chain.

Moreover, the advanced capabilities of digital twins, which create virtual representations of physical processes for simulation and monitoring, empower stakeholders to explore various scenarios without affecting real-world operations (Jagtap et al., 2022). Such simulations aid in validating decisions and promoting proactive strategies to optimize resource allocation. Ultimately, the integration of real-time data visualization tools creates a more cohesive and agile FSC, reinforcing food security through collective insights and efforts.

3.1.6. Enhancing FSC security and transparency

The integration of IoT devices allows real-time data acquisition, monitoring, and storage, ensuring transparency and reducing human errors in food-status monitoring (Addou et al., 2023). Blockchain technology further secures transactions and maintains a tamper-proof record, thereby enhancing trust among the supply chain participants (Kumar & Dwivedi, 2023a).

In smart cities, IoT technologies facilitate the management of the food business by providing real-time monitoring and intelligent vehicle routing, thereby improving the supply chain networks (Girirajan et al., 2024). Additionally, digitization of the FSC in IoT environments helps minimize food waste and manage sustainable supply chains by enabling more connected, faster, and more precise operations (İzmirli et al., 2020).

IoT and blockchain are also crucial in automating business processes in the agricultural FSC, providing real-time monitoring of goods, and securing transactions through smart contracts (Raza et al., 2023). These technologies are essential for addressing the challenges posed by traditional farming methods and the risks highlighted during the Covid-19 pandemic (Wan Mohamad & Rakiman, 2023).

Furthermore, the implementation of IoT in cold supply chains supports the delivery of perishable items by enabling remote monitoring and data logging, thereby ensuring the maintenance of the critical temperature and humidity levels (Sarkar et al., 2022). The overall adoption of IoT and blockchain in the FSC promises enhanced resilience, efficiency, and transparency, although it requires further investigation to overcome the complexities and specific needs of the FSC (Rubee Singh et al., 2023).

IoT-enabled smart FSCs focus on enhancing transparency, security, and efficiency by integrating blockchain technology and smart contracts. For instance, a new model has been designed to provide real-time data acquisition, monitoring, and storage on a tamper-proof blockchain, which significantly improves the tracking of food, money, and information movement within the supply chain (Addou et al., 2023). This model utilizes IoT networks to gather data about food status without human involvement, ensuring transparency and correctness of data through machine learning models.

In smart cities, an IoT-based Dynamical Food Chain of Supply has been proposed, which uses the Fire Hawk Optimization technique to ensure food quality and provide intelligent vehicle routing. This system performs better than the existing methodologies by optimizing the supply chain network with a minimal dataset size (Girirajan et al., 2024).

Furthermore, blockchain and IoT technologies have been applied to secure and smart agricultural FSCs, enhance trust, reduce authentication delays, and improve the computational time and throughput (Kumar & Dwivedi, 2023b). These technologies also support the automation of business processes and the real-time monitoring of goods, which are critical for maintaining product health and the environment throughout the supply chain (Raza et al., 2023). In addition, IoT devices have been utilized in cold supply chains to remotely monitor and log data, thereby ensuring the conservation of temperature and humidity for perishable food items during transport or storage (Sarkar et al., 2022).

IoT-enabled smart FSCs face challenges in ensuring data security and integrity, optimizing blockchain computations, and effectively integrating these technologies (Addou et al., 2023; Girirajan et al., 2024; Kumar & Dwivedi, 2023b). However, they also offer significant opportunities to improve the FSC. Real-time monitoring using IoT devices can enhance food quality and safety by identifying contaminants and optimizing delivery routes (Girirajan et al., 2024). Furthermore, digitization of IoT promotes better inventory management and network design, leading to reduced food waste (İzmirli et al., 2020). Blockchain technology enhances security, transparency, and trust by providing tamper-proof transactional systems (Kumar & Dwivedi, 2023b).

The combined use of IoT and blockchain supports sustainable practices by improving efficiency and reducing environmental impact (Wan Mohamad & Rakiman, 2023). Finally, smart contracts and IoT devices automate processes, reduce human intervention, and increase data integrity (Singh & Raza, 2023).

IoT networks collect data on food status, and machine learning models ensure data accuracy and support decision making. Dynamic vehicle routing and optimization techniques, such as fire-hawk optimization, have been used to improve supply chain efficiency and precision (Girirajan et al., 2024). Business process modeling helps analyze the use of blockchain, smart contracts, and IoT in automating business processes and securing transactions (Raza et al., 2023). These methodologies contribute to the development of more efficient, transparent, and secure FSCs in the face of Industry 4.0 challenges.

3.1.7. Enhancing food traceability and security

The integration of IoT, blockchain technology, and fuzzy logic has revolutionized food traceability and security within the FSC. By leveraging these technologies, various stakeholders, including farmers, distributors, retailers, and regulatory agencies can effectively monitor and manage perishable foods while ensuring the authenticity of their origin. IoT sensors deployed in storage facilities and transportation units track temperature, humidity, and storage duration in real time, helping to prevent spoilage. For example, companies like Maersk and Walmart use IoT-enabled cold chain monitoring to maintain optimal storage conditions for perishable goods, reducing food loss and enhancing consumer confidence in food safety (Duan, Onyeaka, Pang, et al., 2024).

IoT systems also play a crucial role in monitoring environmental conditions that affect agricultural production. Beyond soil moisture levels and harmful metal detection, IoT-enabled smart irrigation systems adjust water distribution based on real-time weather data, significantly improving water-use efficiency and crop yields. Additionally, remote sensing technology helps detect soil nutrient deficiencies, allowing farmers to apply precise fertilizers and reduce environmental impact (Mukherjee et al., 2021). A study by the Food and Agriculture Organization (FAO) found that precision farming techniques powered by IoT have led to a 20 % increase in crop yields while reducing water and fertilizer usage by up to 30 %, demonstrating their tangible impact on agricultural sustainability.

An innovative approach to data-driven optimization in the FSC is Self-adaptive Dynamic Partition Sampling (SDPS), which allows for efficient data collection from distributed sensors. SDPS optimizes sensor sampling rates by dynamically adjusting data collection frequency based on environmental conditions and detected anomalies. This minimizes redundancy while ensuring critical traceability data is recorded accurately (Zhang et al., 2013). In practical terms, SDPS reduces data transmission costs by up to 40 %, while maintaining high accuracy in food provenance tracking, ensuring that food products can be traced back to their exact source with minimal computational overhead.

Furthermore, IoT and machine learning enable the visualization of contamination risks in the FSC. For instance, contamination mapping systems use IoT sensors to detect chemical residues or bacterial contamination in food products. This data is then visualized through real-time dashboards, allowing supply chain managers to identify contamination sources and take corrective actions immediately (Zhang et al., 2013). Nestlé and IBM Food Trust, for example, use IoT-linked blockchain systems to quickly pinpoint contaminated batches of food, reducing the time needed for recalls from several days to mere hours, minimizing health risks and economic losses.

Despite these advancements, significant challenges remain in the implementation of IoT-enabled smart FSC. One primary concern is the complexity of managing vast and heterogeneous supply chains, where multiple players operate at different stages. This complicates data integration, standardization, and real-time decision-making. IoT technologies address this challenge by employing edge computing which processes data at the source rather than relying on cloud networks to improve response times and reduce dependency on centralized databases (Zhang et al., 2013). Additionally, AI-driven anomaly detection algorithms ensure that inconsistent or fraudulent data is flagged before it enters the supply chain record, increasing data reliability.

Another key challenge is ensuring data accuracy while minimizing sampling, as different food types have unique storage and tracking requirements. For example, fresh produce requires continuous monitoring of temperature and humidity, whereas packaged goods may only need periodic verification. IoT-enabled adaptive monitoring systems adjust data collection rates based on the sensitivity of the product, ensuring optimal resource allocation without compromising traceability (Duan, Onyeaka, Pang, et al., 2024).

The integration of blockchain with IoT further enhances security and consumer trust by creating tamper-proof records of food provenance. Blockchain ensures that all transactions, such as farm-to-retailer shipments, are logged immutably, eliminating fraud and enhancing traceability. Companies like Carrefour and Unilever have implemented blockchain-based food tracking systems, allowing consumers to scan QR codes on product packaging to verify sourcing, processing, and quality certifications (Mukherjee et al., 2021). Additionally, smart contracts automate compliance checks and payment processing, reducing administrative overhead of the middlemen in supply chain transactions.

Despite the challenges, the landscape presents substantial opportunities for innovation. Emerging technologies like IoT, blockchain, AI, and fuzzy logic are driving innovation in FSC by improving traceability and decision-making. The enhanced traceability achieved through IoT and blockchain technologies can significantly improve food quality control and safety throughout the supply chain (Duan, Onyeaka, Pang, et al., 2024). By developing decision-support systems that leverage real-time data, farmers can make better-informed decisions, ultimately increasing crop yields and reducing operational costs. Additionally, IoT-driven predictive analytics optimize resource allocation and reduce food waste, further bolstering global food security (Dhal & Kar, 2024).

Methodologically, various approaches continue to enhance IoT-enabled smart FSC, focusing on food security through optimization and interactive decision-making tools. SDPS, for instance, has proven effective in gathering sensor data for accurate food traceability (Zhang et al., 2013). Furthermore, integrating blockchain with IoT sensor modules strengthens supply chain security by ensuring verifiable, tamper-proof data records, facilitating informed decision-making, and identifying food quality degradation risks (Mukherjee et al., 2021).

Additionally, fuzzy logic systems provide advanced monitoring and risk assessment capabilities in agricultural IoT applications. By integrating IoT, blockchain, and AI-driven decision-making tools, stakeholders can create a more sustainable, secure, and efficient FSC, enhancing the capacity to withstand disruptions while meeting increasing global food demands.

3.2. IoT's role in food quality, safety, and monitoring

3.2.1. Enhancements in food safety

Advancements in food safety increasingly depend on the integration of innovative technologies that bolster transparency and traceability throughout the FSC. The incorporation of IoT devices enables the real-time monitoring of food products, ensuring optimal conditions from farm to table. This capability is crucial for preventing potential contamination and spoilage and ultimately protecting consumer health. Furthermore, the integration of blockchain technology significantly enhances food safety by providing a decentralized and immutable ledger that records every transaction in the supply chain. As noted in recent studies, blockchain not only improves transparency and traceability, but also addresses issues surrounding information distribution and compliance with safety standards (Duan, Onyeaka, & Pang, 2024).

Additionally, ongoing challenges such as scalability and regulatory frameworks must be addressed to maximize the potential of these technologies in transforming food safety, as highlighted by the existing Distributed Ledger Technology (DLT) initiatives (Hellani et al., 2020). These enhancements collectively foster a trusted and efficient FSC.

3.2.2. Role of IoT in monitoring food quality and safety standards

Emerging technologies, particularly the IoT, play a pivotal role in ensuring the quality and safety of food throughout the supply chain. By utilizing smart sensors and automated data collection, stakeholders can continuously monitor critical parameters such as temperature, humidity, and contamination levels, thereby enhancing food safety standards. This proactive approach is essential in today's agri-food industry, which faces increasing challenges related to environmental stressors and global crises, as highlighted by the COVID-19 pandemic (Hassoun et al., 2023).

Moreover, effective monitoring can lead to early detection of quality degradation, minimizing the risk of foodborne illnesses and waste. As pointed out in a recent literature review, integrating IoT with pharmaceutical packaging technologies signifies how similar methodologies can reshape FSCs, fostering confidence among consumers and producers alike in the reuse and safe consumption of food products (Hui, Mohammed, Donyai, McCrindle, & Sherratt, 2020). These advances will ultimately contribute to more resilient and sustainable food systems.

3.3. IoT-driven logistics, inventory, and dynamic supply chain optimization

3.3.1. Impact of IoT on logistics and inventory management in the food industry

The integration of the IoT in logistics and inventory management significantly transforms operations within the food industry. By enabling real-time monitoring and data collection, IoT technologies facilitate enhanced visibility throughout the supply chain, allowing businesses to make informed decisions on inventory levels and distribution strategies are essential for minimizing waste and enhancing sustainability efforts. The continuous tracking of food products from farms to tables not only reduces spoilage but also addresses critical challenges such as excess production and inefficient resource allocation. Recent explorations of smart logistical solutions highlight the importance of effective production planning, which, when coupled with IoT capabilities, can lead to optimized inventory management and reduced food waste (Hanis & Fernando, 2024).

The integration of IoT into production planning is achieved through real-time monitoring, predictive analytics, and automated decision-making systems. IoT-enabled sensors and RFID tags track storage conditions, expiration dates, and transportation routes, ensuring that food products are distributed efficiently based on demand forecasts. For instance, companies like Carrefour and Walmart leverage IoT to monitor temperature-sensitive goods, preventing spoilage and ensuring compliance with food safety regulations. Additionally, AI-driven demand prediction models analyze consumer behavior and external factors such as weather conditions to adjust production schedules dynamically, reducing both surplus and shortages.

Moreover, as businesses increasingly adopt innovative technologies, the need for flexibility and adaptability has become paramount to meet changing market demands while maintaining efficiency (Britchenko et al., 2018). By leveraging IoT-integrated production planning, companies can create more responsive, resilient, and sustainable FSCs that enhance profitability while minimizing environmental impact.

Optimization simulations informed by data analytics serve as a transformative force within the FSC, enabling stakeholders to make informed strategic decisions. By integrating real-time data into predictive modeling, these simulations can anticipate fluctuations in demand, adapt to climatic variations, and efficiently allocate resources throughout the supply chain. For example, a responsive agriculture hub leveraging e-commerce platforms demonstrates the potential of data-driven approaches.

As outlined in (Rahman et al., 2024), this model utilizes data analytics and smart logistics to enhance food accessibility and affordability, highlighting how optimization simulations can lead to a more resilient agricultural system. Additionally, with the increasing implementation of smart agriculture technologies, such as IoT devices and precision farming, farmers are better equipped to increase crop yields and optimize input usage (Gürdil, Hidayat, Demirel, & Cevher, 2024). Therefore, the integration of data-driven optimization simulations not only enhances operational efficiency but also strengthens food security in an increasingly complex landscape.

3.3.2. *IoT-based dynamical food chain of supply for smart cities*

The implementation of IoT and blockchain technologies enhances the efficiency, transparency, and safety of FSC. IoT technology aids in real-time monitoring, analysis, and management of the food business, particularly in urban smart cities. For example, smart sensors and RFID tags are used in cold chain logistics to monitor temperature-sensitive food products, ensuring compliance with safety standards and reducing spoilage. Walmart's adoption of IoT and blockchain in its supply chain has significantly improved product traceability, reducing the time required to track contaminated food from 7 days to just 2.2 s. Similarly, Carrefour's blockchain-based traceability system allows consumers to verify product origins by scanning QR codes on food packaging, improving transparency and consumer trust.

An advanced application of IoT in food logistics is the Fire Hawk Optimization technique for intelligent vehicle routing and contamination detection (Girirajan et al., 2024). This algorithm optimizes delivery routes by analyzing real-time traffic data, weather conditions, and perishability factors, ensuring faster and safer transportation of food products. Additionally, Fire Hawk Optimization uses IoT-enabled contamination sensors to detect spoilage risks in transit, allowing for immediate corrective actions that prevent unsafe products from reaching consumers. Studies have shown that this approach reduces delivery time by 15 % and decreases food spoilage by 20 %, making supply chains more resilient and cost-efficient.

The integration of IoT and blockchain has also been shown to improve security, trust, and operational efficiency in agricultural FSCs. By reducing authentication delays and computational time, blockchain ensures secure and verifiable transactions (Kumar & Dwivedi, 2023a, 2023b). For instance, IBM Food Trust has partnered with companies like Nestlé and Unilever to use blockchain for real-time data sharing across the supply chain, eliminating fraud and improving efficiency. Research indicates that blockchain-based systems have reduced transaction times from several days to minutes while enhancing throughput and data integrity (Shardeo et al., 2023).

Smart contracts on blockchain platforms like Ethereum further enhance supply chain security by automating payments, quality verification, and regulatory compliance (Addou et al., 2023). For example, AgriDigital, an Australian agribusiness platform, employs smart contracts to facilitate instant payments upon the verification of grain quality, reducing delays and financial risks for farmers. Similarly, TE-FOOD, a blockchain-powered traceability system, automates compliance checks and food tracking, ensuring that all supply chain stakeholders receive accurate and tamper-proof data.

Regarding sustainability, IoT technologies play a crucial role in minimizing food waste by enabling more connected, faster, and precise supply chain operations (İzmirli et al., 2020). According to a study by the World Economic Forum, IoT-powered cold chain monitoring has helped reduce global food waste by 15 %, primarily by preventing spoilage during storage and transit. In addition, IoT-integrated deep learning techniques help optimize large datasets, improving visibility and provenance in the FSC (Khan et al., 2020). AI-driven analytics have been used by companies like Danone to adjust production based on real-time demand forecasting, reducing excess inventory and minimizing waste.

The integration of IoT and blockchain has revolutionized smart FSCs by enhancing food security, optimizing logistics, and improving decision-making. Studies have demonstrated that these technologies streamline supply chain operations, increase transparency, and foster consumer trust (Girirajan et al., 2024). IoT-based dynamic vehicle routing combined with Fire Hawk Optimization has enhanced food quality by reducing transportation delays, while blockchain ensures data integrity and eliminates manual inefficiencies (Kumar & Dwivedi, 2023a, 2023b). Furthermore, machine learning-enhanced blockchain solutions (Addou et al., 2023) improve data accuracy and transaction security, further strengthening the agricultural FSC. As industries continue to integrate these technologies, the future of FSCs will be increasingly efficient, sustainable, and resilient

Furthermore, in (Singh & Raza, 2023), an IoT and blockchain-based system that focuses on food safety and transparency was proposed. This study reveals a significant shift towards utilizing advanced technologies to address challenges in the FSC, ensuring food safety, quality, and efficient management.

This integration offers numerous opportunities, including enhanced food safety and quality control through real-time monitoring and traceability (Kumar & Dwivedi, 2023a), supply chain efficiency and optimization through IoT and advanced algorithms (Girirajan et al., 2024), waste reduction and sustainability through granular inventory management (İzmirli et al., 2020), transparency and consumer trust through blockchain and smart contracts (Singh & Raza, 2023), and adaptation to Industry 4.0 by integrating IoT with other technologies such as big data and cloud computing (Wan Mohamad & Rakiman, 2023).

Various methodologies have been employed to achieve these advancements, including dynamic vehicle routing with Fire Hawk optimization (Girirajan et al., 2024), blockchain technology for enhanced security and transparency (Kumar & Dwivedi, 2023a), real-time data acquisition and monitoring using blockchain and smart contract integration of IoT networks and machine learning for data analysis and decision-making (Addou et al., 2023), and the development of IoT-based blockchain frameworks with smart contract architecture for regulating food inventory systems (Singh & Raza, 2023). Collectively, these methodologies contribute to the development of connected, transparent, efficient FSCs.

3.4. Industry 4.0 and smart farming for agri-FSC

The integration of IoT with blockchain technology enhances security, transparency, and efficiency in the agri-FSC (Wan Mohamad & Rakiman, 2023). This transformation aligns with Industry 4.0 advancements, which leverage smart farming technologies to optimize agricultural processes. Blockchain plays a crucial role in securing food supply systems by preventing fraud, improving traceability, and ensuring compliance with safety regulations. Additionally, blockchain integration enhances various performance metrics such as trust, data accuracy, and computational efficiency.

The implementation of blockchain in the FSC typically involves decentralized, tamper-proof ledgers that store real-time data collected from IoT-enabled devices, such as RFID tags, GPS trackers, and smart sensors. These devices monitor crucial parameters like temperature, humidity, and handling conditions during transportation and storage. When anomalies are detected, such as a deviation in cold chain logistics, automated alerts can be triggered to prevent spoilage. This process improves efficiency by reducing delays and minimizing food waste.

For example, Walmart and IBM's Food Trust blockchain initiative allows real-time tracking of food products, cutting recall times from days to seconds while ensuring authenticity and compliance with regulatory standards. Similarly, Carrefour's blockchain-based traceability system enables consumers to scan QR codes on food packaging to access verified information about product origins, farming methods, and safety certifications. Beyond improving transparency, blockchain also reduces operational costs by streamlining record-keeping and automating verification processes, eliminating the need for intermediaries.

Furthermore, Girirajan et al. (2024) proposed an IoT-based dynamic FSC model for smart cities that optimizes food quality management and supply chain efficiency. By integrating IoT sensors with blockchain ledgers, companies can create immutable records that enhance accountability and improve decision-making. As the agri-food industry continues to embrace these innovations, the synergy between IoT and blockchain will be instrumental in creating more resilient, transparent, and sustainable food supply networks.

(Addou et al., 2023) discussed the implementation of a blockchain-based model that provides real-time data acquisition and monitoring, enhances transparency and decision-making in the FSC, (Singh & Raza, 2023) and introduces a framework that combines IoT and blockchain to regulate food inventory systems, focusing on safety and transparency. (İzmirli et al., 2020) studied a business model for a digitized FSC that aimed to minimize food waste and manage a sustainable supply chain.

Sarkar et al. (2022) focused on managing the cold supply chain, proposed a low-cost monitoring device that ensures the conservation of temperature and humidity for perishable items, (Raza et al., 2023) and critically examined the integration of blockchain, smart contracts, and IoT to automate business processes and secure transactions in the agricultural FSC. (Nechifor et al., 2014) developed an IoT-enabled infrastructure for smart transportation applications that supported the monitoring of perishable goods during transportation.

IoT-enabled smart FSCs have focused on enhancing security, transparency, and efficiency by integrating blockchain technology and advanced optimization techniques. Blockchain technology has increasingly been adopted to improve the security and transparency of FSCs. For instance, blockchain-based systems have been developed to enhance the integrity, confidentiality, and throughput of FSCs, providing better trust and computational time performance than the existing systems (Shardeo et al., 2023). Additionally, blockchain and smart contracts are used to monitor the health and environment of products throughout the supply chain, ensuring secure transactions and the real-time monitoring of goods (Raza et al., 2023).

IoT technologies are also being implemented to automate and optimize various aspects of the FSC. For example, IoT devices are used in smart farming to minimize human involvement in data collection, recording, and verification, thereby transforming traditional agricultural practices (Kumar & Dwivedi, 2023a, 2023b). In urban settings, IoT-based systems have been suggested for dynamic FSC management, utilizing techniques such as Fire Hawk Optimization to ensure food quality and provide intelligent vehicle routing (Girirajan et al., 2024). Moreover, IoT and blockchain integration are being explored to regulate food inventory systems, focusing on the safety and nature of the items delivered to consumers. This integration uses IoT and IoT-based blockchain with a smart contract architecture to enhance the trust, reliability, and transparency of the food chain management systems (Singh & Raza, 2023).

In addition to these technological advancements, specific applications, such as cold supply chain management, have been addressed by deploying low-cost IoT devices capable of monitoring and logging data in the cloud, which is crucial for the conservation of temperature and humidity in the storage of perishable items (Sarkar et al., 2022).

4. Discussions and recommendations

The content analysis sections showed that while IoT technologies offer transformative potential for optimizing FSCs, their adoption is uneven and faces several critical challenges. IoT has revolutionized the sector by enhancing efficiency through automated monitoring and data-driven decision-making, improving traceability with blockchain integration, increasing transparency by enabling real-time tracking, and promoting sustainability through precision resource management. The reviewed studies highlight these benefits across various stages of the FSC. However, they also reveal significant variations in implementation between developed and developing regions, with advanced IoT systems integrating AI and blockchain being more common in high-resource settings, whereas low-resource contexts face issues related to cost, infrastructure, and digital readiness (Wan Mohamad & Rakiman, 2023). Based on these findings, this section discusses the main opportunities and benefits of IoT, outlines key challenges and barriers to its adoption, proposes directions for future research, and offers practical managerial and policy insights to enable more effective and widespread IoT deployment in the food sector.

4.1. Opportunities and benefits of IoT in the FSC

Fig. 5 illustrates the role of IoT in optimizing the FSC across different stages, from farming to retail. It highlights how IoT sensors and drones enhance precision agriculture by enabling real-time monitoring of soil health and crop growth, allowing farmers to detect nutrient deficiencies and optimize irrigation, as seen in the implementation of John Deere's precision agriculture technologies. In processing and manufacturing, IoT automation improves food safety by detecting contaminants in real-time, as exemplified by Tyson Foods' use of sensor-driven quality control systems, which minimize waste and boost operational efficiency The shipping and storage phase benefits from IoT-enabled cold chain management, where advanced IoT sensors, RFID tags, and GPS tracking systems continuously monitor temperature, humidity, and location to prevent spoilage. IoT-based temperature loggers, such as Bluetooth-enabled data loggers and wireless sensor networks, provide real-time temperature readings and send alerts if deviations occur, ensuring prompt corrective actions. Additionally, blockchain-integrated tracking enhances transparency and traceability by securely recording temperature data throughout the supply chain, reducing fraud and ensuring

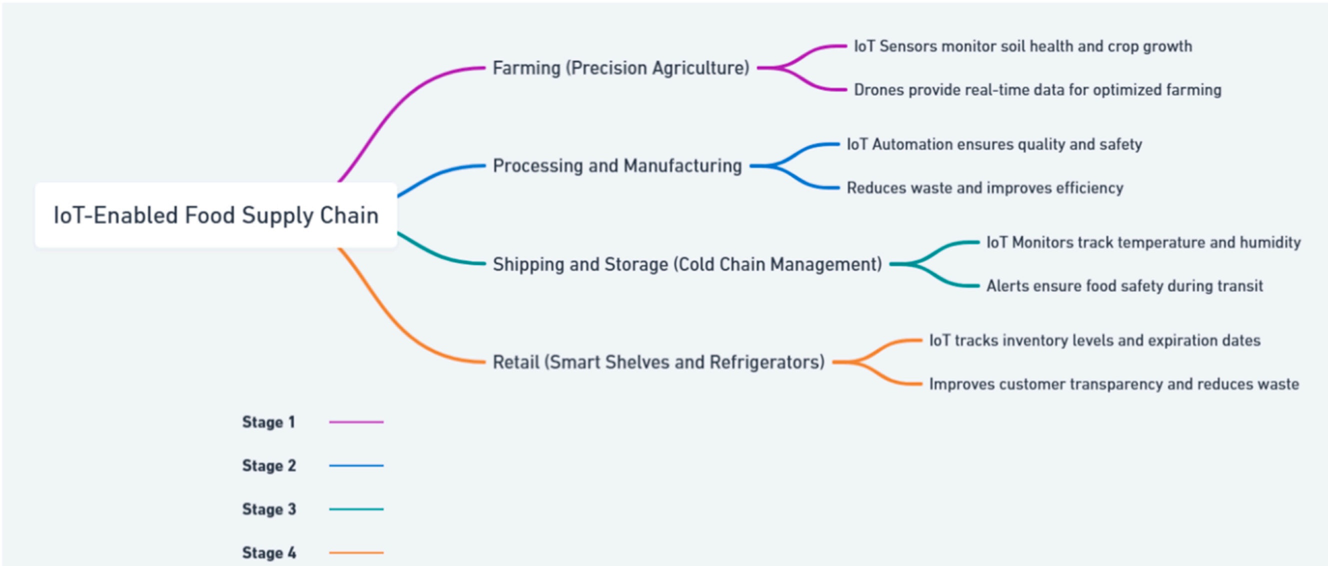

Fig. 5. IoT-Enabled FSC optimization.

compliance with food safety standards.

Intelligent packaging solutions, such as smart labels, near-field communication (NFC) tags, and time-temperature indicators (TTIs), play a crucial role in preserving product integrity by dynamically assessing freshness and signaling when storage conditions become sub-optimal. These innovations not only minimize spoilage and reduce food waste but also enhance supply chain efficiency by optimizing logistics, improving inventory turnover, and ensuring consumers receive high-quality products with verified storage histories.

Finally, at the retail level, smart shelves and IoT-powered refrigerators, such as Amazon Go's automated checkout systems, help manage inventory, reduce waste, and improve customer transparency by ensuring accurate product tracking and expiration date management. Smart shelves, equipped with RFID tags and weight sensors, automatically detect stock levels and send real-time alerts to store managers when products need replenishment, preventing stockouts and over-stocking. For instance, Walmart uses smart shelving systems to monitor product availability and improve restocking efficiency, ensuring a seamless shopping experience.

Similarly, IoT-powered refrigerators, like those used by grocery retailers such as Tesco and Carrefour, incorporate temperature sensors and automated inventory tracking to maintain optimal storage conditions for perishable goods. These refrigerators notify staff when temperature fluctuations occur, reducing spoilage and ensuring food safety. Additionally, consumer-facing applications linked to these systems allow shoppers to check product freshness and availability in real time, enhancing convenience and trust. By leveraging these technologies, retailers can optimize stock management, minimize food waste, and offer a more efficient and transparent shopping experience.

The integration of IoT technologies presents significant opportunities for enhancing efficiency, transparency, traceability, and sustainability across FSCs. The reviewed studies consistently highlight IoT's capacity to transform traditional supply chain operations by enabling real-time monitoring, data-driven decision-making, and predictive analytics (Mukherjee et al., 2021; Sarkar et al., 2022). For instance, precision agriculture benefits from IoT sensors that monitor soil moisture, temperature, and crop health, optimizing resource use and improving yields (Mukherjee et al., 2021).

In food processing and manufacturing, IoT-enabled automation systems, such as smart quality control sensors and AI-powered sorting machines, enhance food safety and quality by detecting contaminants, monitoring production conditions, and ensuring compliance with health regulations. For example, automated vision systems powered by IoT identify defects in food products, preventing contaminated or sub-standard items from reaching consumers. Additionally, real-time data from IoT sensors allows manufacturers to adjust processing parameters dynamically, reducing overproduction, minimizing ingredient waste, and optimizing energy consumption.

Furthermore, IoT-enabled cold chain systems preserve the freshness of perishable goods through real-time temperature monitoring, thereby minimizing spoilage (Sarkar et al., 2022). These systems use connected sensors to track environmental conditions during transportation and storage, sending alerts if temperature deviations occur. This proactive monitoring not only prevents food loss but also improves compliance with food safety regulations and extends shelf life, ultimately enhancing supply chain efficiency and reducing economic losses.

At the retail level, IoT fosters smart inventory systems such as intelligent refrigerators and shelves, enhancing stock management and improving customer satisfaction. Consumers also benefit from enhanced traceability through IoT tracking systems that provide detailed product journeys, building trust and ensuring food safety. Blockchain-integrated IoT solutions allow consumers to scan QR codes on product packaging to access real-time data about the origin, processing, and transportation history of their food items. Retailers such as Carrefour and Walmart have implemented these traceability systems, enabling customers to verify product authenticity, ethical sourcing, and compliance with food safety standards. These technologies not only enhance transparency but also empower consumers to make informed purchasing decisions.

For producers, IoT-enabled tracking systems optimize supply chain visibility by continuously monitoring temperature, humidity, and handling conditions during transportation and storage. This ensures compliance with food safety regulations, minimizes losses due to spoilage or mishandling, and allows for proactive quality control measures. Additionally, IoT-powered predictive analytics help producers streamline logistics, prevent overstocking, and implement just-in-time inventory management, reducing food loss and waste (FLW). The integration of IoT in retail and supply chains ultimately enhances transparency, strengthens consumer confidence, and drives greater operational efficiency while supporting broader sustainability initiatives (İzmirli et al., 2020).

The use of interactive simulation tools and AI-based models also enables stakeholders to assess various scenarios, leading to improved responsiveness to supply and demand fluctuations.

4.2. Challenges and barriers to IoT adoption in the FSC

Despite these promising opportunities, several challenges hinder widespread IoT adoption in FSCs, particularly in developing regions. One of the most significant barriers is the high cost of implementation, which restricts access for small-scale farmers and enterprises (Wan Mohamad & Rakiman, 2023). Moreover, infrastructure limitations, such as poor internet connectivity and unreliable energy supply, create further obstacles to IoT deployment in rural areas.

Data privacy and cybersecurity concerns are also major challenges, as IoT systems often involve sensitive data exchange (Raza et al., 2023). The lack of standardized interoperability frameworks impedes seamless communication between devices, limiting scalability (Fang et al., 2023). Additionally, consumer trust issues around data use and transparency must be addressed to foster broader acceptance of IoT-based solutions. Without effective governance and policy support, these barriers may prevent the realization of IoT's full potential in transforming food systems.

4.3. Managerial and policy insights

For IoT technologies to fully realize their potential in transforming FSCs, targeted managerial and policy interventions are necessary. Managers and stakeholders should focus on integrating real-time monitoring systems with other strategies for reducing food waste and improving operational efficiency. These systems must be designed to align with local contexts and stakeholder capacities, ensuring usability and affordability.

Policymakers should prioritize the development of supportive infrastructure, including reliable internet and energy access, particularly in underserved regions. There is also a need for capacity-building programs to train stakeholders, especially smallholder farmers, in adopting and managing IoT systems. These efforts can be supplemented with public-private partnerships to accelerate technology deployment.

Moreover, collaboration among stakeholders, including technology providers, farmers, manufacturers, and retailers, is essential to create a connected and data-driven supply chain ecosystem. Multi-stakeholder engagement will foster trust, standardization, and innovation. For instance, supporting blockchain integration can enhance transparency and traceability, while collaborative development of interoperable systems can improve efficiency and synergy across supply chain stages.

From a sustainability perspective, managers should align IoT applications with environmental goals, such as reducing greenhouse gas emissions and minimizing resource waste. Incorporating AI and machine learning into IoT systems can further refine decision-making, enabling dynamic responses to shifting supply and demand conditions.

5. Conclusion and future directions

5.1. Conclusion

This study confirms IoT's capacity to enhance efficiency yet highlights the urgent need for cost-effective solutions in developing regions. Through a bibliometric analysis and systematic review of recent literature from 2018 to 2024, this paper has identified how IoT applications, including real-time monitoring, precision agriculture, and cold chain management, contribute to enhancing efficiency, improving traceability, optimizing resource allocation, and promoting sustainability throughout the FSC. By enabling data-driven decision-making and improving transparency, IoT technologies offer effective solutions for reducing food waste, ensuring food safety, and strengthening consumer trust.

However, the analysis also underscores that IoT adoption is accompanied by critical challenges that hinder its broader implementation. These include high costs, infrastructure limitations, data privacy and security concerns, and the lack of standardized frameworks for device interoperability. Addressing these barriers will require collaborative efforts from researchers, policymakers, and industry stakeholders to ensure that IoT solutions are scalable, secure, and accessible to diverse actors, including those in resource-constrained settings.

In summary, the findings of this study confirm that IoT technologies play a pivotal role in enhancing the efficiency, transparency, and sustainability of the FSC, while also supporting broader food security objectives. Yet, realizing their full potential will depend on overcoming the identified challenges through coordinated and sustained efforts. By fostering such collaboration, IoT can serve as a cornerstone for building more resilient and sustainable food systems capable of meeting the demands of a rapidly changing global environment.

5.2. Future research opportunities

To overcome these barriers and maximize IoT's transformative role in FSCs, several research avenues need to be pursued:

First, cost-effective and user-friendly IoT solutions should be developed, especially for smallholder farmers and businesses with limited resources. For example, affordable cold chain monitoring devices can make IoT more accessible (Sarkar et al., 2022). Integrated frameworks that combine IoT with complementary technologies such as blockchain, AI, and machine learning can improve traceability, optimize logistics, and enhance food safety (Addou et al., 2023; Girirajan et al., 2024).

Second, research should focus on addressing data privacy and security through robust governance frameworks and encryption mechanisms. Blockchain-based smart contracts offer a promising pathway for ensuring transparency while mitigating data security risks (Addou et al., 2023).

Third, there is a need to establish global standards and interoperability protocols for IoT systems to facilitate large-scale adoption and integration (Fang et al., 2023). Furthermore, empirical studies that quantify the impact of IoT on food security, sustainability, and efficiency are essential for evidence-based policymaking.

Finally, tailored solutions for different regions are required to bridge the digital divide between developed and developing countries, ensuring equitable access to IoT technologies.

CRediT authorship contribution statement

Mona Jabor Al-Thani: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Majed Hadid:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Adel Elomri:** Writing – review & editing, Visualization, Supervision, Funding acquisition, Conceptualization. **Regina Padmanabhan:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Laoucine Kerbache:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Funding statement

Research reported in this publication was supported by the Qatar Research Development and Innovation Council under Grant MME02-1004-200041. The content is solely the responsibility of the authors and does not necessarily represent the official views of the Qatar Research Development and Innovation Council.

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.

Data availability

The research data are available upon reasonable request.

References

Addou, K., El Ghoumari, M. Y., Achkdir, S., & Azzouazi, M. (2023). A decentralized model to ensure traceability and sustainability of the food supply chain by combining blockchain, IoT, and machine learning. *Mathematical Modeling and Computing, 10*(2). https://doi.org/10.23939/mmc2023.02.498

Adebunmi Okechukwu, Adewusi, Njideka Rita, Chiekezie, & Nsisong Louis, Eyo-Udo (2023). Blockchain for cybersecurity in agriculture: a decentralized approach to data protection. *International Journal of Applied Research in Social Sciences, 5*(10), Article 709723. https://doi.org/10.51594/ijarss.v5i10.1483

Ahmadzadeh, S., Ajmal, T., Ramanathan, R., & Duan, Y. (2023). A comprehensive review on food waste reduction based on IoT and big data technologies. *Sustainability (Switzerland), 15*(4). https://doi.org/10.3390/su15043482

Araújo, S. O., Peres, R. S., Barata, J., Lidon, F., & Ramalho, J. C. (2021). Characterising the agriculture 4.0 landscape—emerging trends, challenges and opportunities. *Agronomy, 11*(4). https://doi.org/10.3390/agronomy11040667

Ben-Daya, M., Hassini, E., Bahroun, Z., & Banimfreg, B. H. (2020). The role of Internet of things in food supply chain quality management: A review. *Quality Management Journal, 28*(1). https://doi.org/10.1080/10686967.2020.1838978

Bhat, S. A., Huang, N. F., Sofi, I. B., & Sultan, M. (2021). Agriculture-Food supply chain management based on blockchain and IoT: A narrative on enterprise blockchain interoperability. *Agriculture 2022, 12*(1). https://doi.org/10.3390/AGRICULTURE12010040

Bhatlawande, A. R., Ghatge, P. U., Shinde, G. U., Anushree, R. K., & Patil, S. D. (2024). Unlocking the future of smart food packaging: Biosensors, IoT, and nano materials. *Food Science and Biotechnology, 33*(5). https://doi.org/10.1007/s10068-023-01486-9

Bisht, D., Singh, R., Gehlot, A., Akram, S. V., Singh, A., Montero, E. C., … Twala, B. (2022). Imperative role of integrating digitalization in the firms finance: A technological perspective. *Electronics (Switzerland), 11*(19). https://doi.org/10.3390/electronics11193252

Botín-Sanabria, D. M., Mihaita, S., Peimbert-García, R. E., Ramírez-Moreno, M. A., Ramírez-Mendoza, R. A., & Lozoya-Santos, J. de J. (2022). Digital twin technology challenges and applications: A comprehensive review. *Remote Sensing, 14*(6). https://doi.org/10.3390/rs14061335

Britchenko, I., Cherniavska, T., & Cherniavskyi, B. (2018). *Blockchain Technology into the Logistics Supply chain Implementation effectiveness*.

Casino, F., Kanakaris, V., Dasaklis, T. K., Moschuris, S., Stachtiaris, S., Pagoni, M., & Rachaniotis, N. P. (2020). Blockchain-based food supply chain traceability: A case study in the dairy sector. *International Journal of Production Research, 59*(19). https://doi.org/10.1080/00207543.2020.1789238

Dadi, V., Nikhil, S. R., Mor, R. S., Agarwal, T., & Arora, S. (2021). Agri-food 4.0 and innovations: Revamping the supply chain operations. *Production Engineering Archives, 27*(2). https://doi.org/10.30657/pea.2021.27.10

Dattatraya Rankhamb, Dinesh, Raut, Surekha Ramesh, & Velapure, Amol Suresh (2024). Smart agriculturing based on KSK approach: a novel AI-Driven-IoT(AIIoT) based Decision-Making approach. *International Journal of Advanced Research in Science, Communication and Technology, 347361*. https://doi.org/10.48175/IJARSCT-19764

Dhal, S. B., & Kar, D. (2024). Transforming agricultural productivity with AI-driven forecasting: Innovations in food security and supply chain optimization. *MDPI Forecasting, 6* (INL/JOU-24-81560-Rev000).

Duan, K., Onyeaka, H., & Pang, G. (2024). Leveraging blockchain to tackle food fraud: Innovations and obstacles. *Journal of Agriculture and Food Research, Elsevier B.V.*. https://doi.org/10.1016/j.jafr.2024.101429

Duan, K., Onyeaka, H., Pang, G., & Meng, Z. (2024). Pioneering food safety: Blockchain's integration in supply chain surveillance. *Journal of Agriculture and Food Research, 18*. https://doi.org/10.1016/j.jafr.2024.101281

Dutta, P.K., & Mitra, S. *Application of Agricultural Drones and IOT to understand Food Supply Chain during post COVID-19*, Agricultural informatics: automation using the IoT and machine learning, 67-87, doi.org/10.1002/9781119769231.ch4.

Fang, M., Liu, F., Xiao, S. S., & Park, K. (2023). Hedging the bet on digital transformation in strategic supply chain management: A theoretical integration and an empirical test. *International Journal of Physical Distribution and Logistics Management, 53*(4), Article 512531. https://doi.org/10.1108/IJPDLM-12-2021-0545

FAO. (2009). Global agriculture towards 2050. Consulté 18 Mars 2025. *à l'Adresse*. ⟨https://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf⟩.

FAO. (2017). The future of food and agriculture: trends and challenges | agrifood economics | food and agriculture organization of the united nations. Consulté 18 Mars 2025. *à l'Adresse*. ⟨https://www.fao.org/agrifood-economics/publications/detail/en/c/1475516/⟩.

FAO. (2022). The future of food and agriculture – drivers and triggers for transformation. *The Future of Food and agriculture – Drivers and triggers for Transformation*. https://doi.org/10.4060/CC0959EN

Fatimah, Y. A., Govindan, K., Murniningsih, R., & Setiawan, A. (2020). Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia. *Journal of Cleaner Production, 269*. https://doi.org/10.1016/j.jclepro.2020.122263

Ferhat Taleb, S., Benalia, N. E. H., & Sadoun, R. (2023). Evolutionary algorithm applications for IoTs dedicated to precise irrigation systems: State of the art. *Evolutionary Intelligence, 16*(2). https://doi.org/10.1007/s12065-021-00676-w

Gaudio, M. T., Chakraborty, S., & Curcio, S. (2022). Agri-food supply-chain traceability: a multi-layered solution. *2022 ieee intl conf on dependable, autonomic and secure computing, intl conf on pervasive intelligence and computing. Intl Conf on Cloud and Big Data Computing, Intl Conf on Cyber Science and Technology Congress (DASC/PiCom/CBDCom/CyberSciTech)*. IEEE. https://doi.org/10.1109/DASC/PiCom/CBDCom/Cy55231.2022.9928017, 15.

Girirajan, B., Naick, B. R., Al-Jawahry, H. M., Revanasiddappa, & Rana, Veer Samara Sihman Bharattej, R. (2024). A management of food supply chain in sustainable smart cities using fire hawk optimization. *2nd IEEE International Conference on Data Science and Information System, ICDSIS 2024. Institute of Electrical and Electronics Engineers Inc*. https://doi.org/10.1109/ICDSIS61070.2024.10594587

Goyal, A., Kanyal, H. S., & Sharma, B. (2023). Analysis of IoT and blockchain technology for agricultural food supply chain transactions. *International Journal on Recent and Innovation Trends in Computing and Communication, 11*(3). https://doi.org/10.17762/ijritcc.v11i3.6342

Gürdil, G. A. K., Hidayat, B., Demirel, B., & Cevher, E. Y. (2024). PERTANIAN TROPIK smart agriculture application in rice cultivation. *Jurnal Online Pertanian Tropik, 11*(1), 9021. https://doi.org/10.32734/jpt.v11i2.17832

Gurkan A. K, G., Benny, H., Demirel, B., & Cevher, E. Y. (2024). Smart agriculture application in rice cultivation. *Jurnal Online Pertanian Tropik, 11*(2), 921. https://doi.org/10.32734/jopt.v11i2.17832

Hanis, M. H., & Fernando, Y. (2024). Smart logistics solutions for reducing food waste: A case of d nipah catering. *International Journal of Industrial Management, 18*(1). https://doi.org/10.15282/ijim.18.1.2024.10404

Hassoun, A., Marvin, H. J. P., Bouzembrak, Y., Barba, F. J., Castagnini, J. M., Pallarés, N., … Regenstein, J. M. (2023). Digital transformation in the agri-food industry: Recent applications and the role of the COVID-19 pandemic. *Frontiers in Sustainable Food Systems, 7*. https://doi.org/10.3389/fsufs.2023.1217813

Hellani, H., Sliman, L., Samhat, A. E., & Exposito, E. (2020). Overview on the blockchain-based supply chain systematics and their scalability tools. *Emerging Science Journal, 4* (Special Issue). https://doi.org/10.28991/esj-2021-SP1-04

Huang, P., & Fang, J. (2024). Multi-objective sustainable supply chain network planning based on proximity optimization with hybrid genetic algorithm variable neighborhood search strategy. *IEEE Access*. https://doi.org/10.1109/ACCESS.2024.3479282

Hui, T. K. L., Mohammed, B., Donyai, P., McCrindle, R., & Sherratt, R. S. (2020). Enhancing pharmaceutical packaging through a technology ecosystem to facilitate the reuse of medicines and reduce medicinal waste. *Pharmacy, 8*(2). https://doi.org/10.3390/pharmacy8020058

İzmirli, D., Ekren, B. Y., & Kumar, V. (2020). Inventory share policy designs for a sustainable omni-chanel e-commerce network. *Sustainability (Switzerland), 12*(23), 116. https://doi.org/10.3390/su122310022

Jagtap, S., Rahimifard, S., & Duong, L. N. K. (2022). Real-time data collection to improve energy efficiency: A case study of food manufacturer. *Journal of Food Processing and Preservation, 46*(8). https://doi.org/10.1111/jfpp.14338

Kale, S., Apte, A., Raut, S., Dorage, S., & Bhadkumbhe, S. M. (2019). Blockchain based smart Agri-Food supply chain management. *International Journal of Research in Engineering, Science and Management, 2*(6).

Khan, P. W., Byun, Y.-C., & Park, N. (2020). IoT-blockchain enabled optimized provenance system for food industry 4.0 using advanced deep learning. *Sensors (Switzerland), 20*(10). https://doi.org/10.3390/s20102990

Kim, C. Y., Ng, B. C. K., Sahni, J., Samian, N., & Seah, W. K. G. (2023). Blockchain network platform for IoT data integrity and scalability. *IEEE International Conference on Software Quality, Reliability and Security, QRS*. https://doi.org/10.1109/QRS60937.2023.00025

Kumar, D., & Dwivedi, R. K. (2023a). Blockchain and IoT based smart agriculture and food supply chain system. *Proceedings of the International Conference on Intelligent and Innovative Technologies in Computing, Electrical and Electronics, ICIITCEE 2023*. https://doi.org/10.1109/IITCEE57236.2023.10090897

Kumar, D., & Dwivedi, R. K. (2023b). Designing a secure food supply chain system using blockchain in agricultural IoT. *2023. International Conference on Computational Intelligence, Communication Technology and Networking, CICTN 2023*. https://doi.org/10.1109/CICTN57981.2023.10141423

Lee, C. C., Zeng, M., & Luo, K. (2024). How does climate change affect food security? Evidence from China. *Environmental Impact Assessment Review, 104*. https://doi.org/10.1016/j.eiar.2023.107324

Luque, A., Peralta, M. E., de las Heras, A., & Córdoba, A. (2017). State of the industry 4.0 in the andalusian food sector. *Procedia Manufacturing, 13*. https://doi.org/10.1016/j.promfg.2017.09.195

Mayring, P., & Fenzl, T. (2019). Qualitative inhalts analyse. *Dans Handbuch Methoden der empirischen Sozialforschung*. https://doi.org/10.1007/978-3-658-21308-4_42

Mehannaoui, R., Mouss, K. N., & Aksa, K. (2023). IoT-based food traceability system: Architecture, technologies, applications, and future trends. *Food Control, 145*. https://doi.org/10.1016/j.foodcont.2022.109409

Mohammed, C. P., & Chopra, S. R. (2023). Blockchain security implementation using python with NB-IoT deployment in food supply chain. *2023. International Conference on Emerging Smart Computing and Informatics, ESCI 2023*. https://doi.org/10.1109/ESCI56872.2023.10100139

Morales, M. L. V., & Elkader, M. A. A. (2020). Logistics 4.0 technologies in agriculture systems: potential impacts in the sdg. *towards the digital world and industry x.0. Proceedings of the 29th International Conference of the International Association for Management of Technology, IAMOT 2020*.

Moudoud, H., Cherkaoui, S., & Khoukhi, L. (2019). An IoT blockchain architecture using oracles and smart contracts: the Use-Case of a food supply chain. *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC, 2019-*

September. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/PIMRC.2019.8904404

Mukherjee, U., Dutta, S., & Bandyopadhyay, S. K. (2021). Assembling blockchain and IoT for smart Food-Supply chain. *Asian Journal of Advances in Agricultural Research*. https://doi.org/10.9734/ajaar/2021/v16i330177

Nechifor, S., Târnaucə, B., Sasu, L., Puiu, D., Petrescu, A., Teutsch, J., & Moldoveanu, F. (2014). Autonomic monitoring approach based on CEP and ML for logistic of sensitive goods. *INES 2014 - IEEE 18th International Conference on Intelligent Engineering Systems, Proceedings*. https://doi.org/10.1109/INES.2014.6909343

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., … Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *International Journal of Surgery, 88*, Article 105906. https://doi.org/10.1016/j.ijsu.2021.105906

Quy, V. K., Hau, N. Van, Anh, D. Van, Quy, N. M., Ban, N. T., Lanza, S., & Muzirafuti, A. (2022). IoT-Enabled smart agriculture: architecture, applications, and challenges. *Applied Sciences (Switzerland), 12*(7). https://doi.org/10.3390/app12073396

Rahman, W. N. W. A., Zulkifli, W. N. W., Zainuri, N. N., & Anwar, H. A. K. (2024). Model for responsive agriculture hub via e-Commerce to sustain food security. *International Journal of Advanced Computer Science and Applications, 15*(5), Article 355368. https://doi.org/10.14569/IJACSA.2024.0150535

Raza, Z., Haq, I. U., & Muneeb, M. (2023). Agri-4-All: a framework for blockchain based agricultural food supply chains in the era of fourth industrial revolution. *IEEE Access, 11*, Article 2985129867. https://doi.org/10.1109/ACCESS.2023.3259962

Sarkar, S., Akshatha, K. S., Saurabh, A., Samanvitha, B., & Sarwar, M. F. (2022). IoT enabled cold supply chain monitoring system. *2022 IEEE 3rd Global Conference for Advancement in Technology, GCAT 2022*. https://doi.org/10.1109/GCAT55367.2022.9972137

Shardeo, V., Patil, A., Dwivedi, A., & Madaan, J. (2023). Modelling of critical success factors for blockchain technology adoption readiness in the context of agri-food supply chain. *International Journal of Industrial and Systems Engineering, 43*(1), 80102. https://doi.org/10.1504/IJISE.2021.10037223

Shermin Voshmgir, T. N., & Rammel, M. W. C. (2019). *Sustainable Development Report: Blockchain, the Web3 the SDGs*.

Singh, Rajesh, Akram, S. V., Gehlot, A., Buddhi, D., Priyadarshi, N., & Twala, B. (2022). Energy system 4.0: Digitalization of the energy sector with inclination towards sustainability. *Sensors, 22*. https://doi.org/10.3390/s22176619

Singh, Rubee, Khan, S., Dsilva, J., & Centobelli, P. (2023). Blockchain integrated IoT for food supply chain: A grey based Delphi-DEMATEL approach. *Applied Sciences (Switzerland), 13*(2). https://doi.org/10.3390/app13021079

Singh, A. K., & Raza, Z. (2023). A framework for IoT and blockchain based smart food chain management system. *Concurrency and Computation: Practice and Experience, 35*(4). https://doi.org/10.1002/cpe.7526

Subashini, B., & Hemavati, D. (2022). Blockchain and IoT's role in agri food supply chain traceability. *9th IEEE Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering, UPCON 2022*. https://doi.org/10.1109/UPCON56432.2022.9986425

Suciu, G., Pop, I., Pasat, A., Calescu, S., Vatasoiu, R., & Suciu, I. (2021). Digital solutions for smart food supply chain. *IEEE 27th International Symposium for Design and Technology in Electronic Packaging, SIITME 2021 - Conference Proceedings, 2021*. https://doi.org/10.1109/SIITME53254.2021.9663672

Teh, D., & Rana, T. (2023). The use of Internet of things, big data analytics and artificial intelligence for attaining UN's SDGs. *Dans Handbook of Big Data and Analytics in Accounting and Auditing*. https://doi.org/10.1007/978-981-19-4460-4_11

Toromade, Adekunle Stephen, Soyombo, Deborah Aanuoluwa, Kupa, Eseoghene, & Ijomah, Tochukwu Ignatius (2024). Technological innovations in accounting for food supply chain management. *Finance Accounting Research Journal, 6*(7), Article 12481258. https://doi.org/10.51594/farj.v6i7.1315

Vodă, A. D. S., Tudor, A. I. M., Chiţu, I. B., Dovleac, L., & Brătucu, G. (2021). IoT technologies as instruments for SMEs' innovation and sustainable growth. *Sustainability (Switzerland), 13*(11). https://doi.org/10.3390/su13116357

Wan Mohamad, W. M., & Rakiman, U. S. (2023). Intergrative review of iot implementation in agri-food supply chain: Findings and analysis. *International Journal of Entrepreneurship and Management Practices, 6*(23). https://doi.org/10.35631/ijemp.623003

Wang, Y., Su, Z., Zhang, N., Xing, R., Liu, D., Luan, T. H., & Shen, X. (2023). A survey on metaverse: Fundamentals, security, and privacy. *IEEE Communications Surveys and Tutorials, 25*(1). https://doi.org/10.1109/COMST.2022.3202047

Zhang, Q., Huang, T., Zhu, Y., & Qiu, M. (2013). A case study of sensor data collection and analysis in smart city: Provenance in smart food supply chain. *International Journal of Distributed Sensor Networks, 9*(11). https://doi.org/10.1155/2013/382132