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REVIEW

Transforming Agrifood Supply Chains with Digital Technologies: a Systematic Review of Safety and Quality Risk Management

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Abstract

The increasing complexity and globalization of agrifood supply chains (AFSCs) issue significant challenges to ensuring food safety and quality. These risks, ranging from microbial contamination and chemical hazards to traceability failures and food fraud, need innovative and scalable risk management strategies. This systematic literature review synthesizes findings from 164 peer-reviewed articles published between 2011 and 2023, investigating the role of Industry 4.0 (I4.0) technologies in managing food safety and quality risks across the AFSC. Technologies analyzed include artificial intelligence (AI), machine learning (ML), Blockchain (BC), Internet of Things (IoT), big data (BD), digital twins (DT), robotics, and more. Findings reveal that I4.0 technologies enhance real-time monitoring, predictive analytics, traceability, and process automation, leading to reduced contamination risks, operational efficiency, and improved stakeholder trust. AI and big data support early hazard detection and decision-making and blockchain and IoT improve traceability and transparency, while digital twins simulate disruptions and optimize safety–critical operations. Despite the benefits demonstrated, key barriers exist, including high implementation costs, data interoperability issues, and limited digital literacy among small and medium-sized enterprises. The review highlights the need for integrated, sector-specific applications, regulatory adaptation, and interdisciplinary collaboration to overcome these obstacles. Future research should focus on scalable, secure, and sustainable solutions, particularly those that empower stakeholders and enhance supply chain resilience. This study provides a comprehensive overview of digital transformation trends in food safety, offering actionable insights for industry practitioners, researchers, and policymakers aiming to foster safer and more transparent agrifood systems.

Keywords Agrifood Supply Chains (AFSCs) · Safety and Quality Risks · Industry 4.0 Technologies (I4.0)

Extended author information available on the last page of the article

Abbreviations

ADAT	Advanced data analytic techniques
AFSCs	Agrifood supply chains
AI	Artificial intelligence
AR	Augmented reality
BC	Blockchain
BD	Big data
CC	Cloud computing
CPS	Cyber physical systems
DL	Deep learning
DT	Digital twins
EHS	Environment, health and safety
GIS	Geographical information system
GMP	Good manufacturing practices
GPS	Global positioning system
HACCP	Hazard analysis critical control point
I4.0	Industry 4.0
ICT	Information communication technology
ML	Machine learning
PLF	Precision livestock farming
QR	Quick response
RASFF	Rapid alert system for food and feed
Rbs	Robotics
RFID	Radio frequency identification
SMEs	Small and medium-sized enterprises
VR	Virtual reality
XAI	Explainable AI

1 Introduction

Ensuring food quality and safety in agrifood supply chains is a global priority. Every year, an estimated 600 million people fall ill from eating contaminated food, with hundreds of thousands of fatalities [1]. Supply chains for dairy, meat, grains, fresh produce, and other foods face diverse risks, from microbial contamination and spoilage to fraud and supply disruptions. Over the last decade, Industry 4.0 technologies have emerged as promising tools to manage these risks by making food supply chains smarter, more transparent, and more responsive. Industry 4.0 refers to a suite of digital and automation technologies, including the Internet of Things (IoT), blockchain, artificial intelligence (AI), robotics, big data analytics, digital twins, cloud computing, cyber-physical systems (CPS), and more—which integrate physical and digital processes [1, 2]. These technologies have been applied across all agrifood sectors, from farm production to food processing and distribution, with the aim of improving quality control, traceability, and safety management. Recent reviews indicate that such digital solutions can increase food safety and traceability while improving quality and reducing waste [3]. In this systematic literature review, we synthesize peer-reviewed research from the past ten years on how Industry 4.0 technologies are being used worldwide to mitigate quality and safety risks in agri-food supply chains. We aim to examine the applications of each major Industry 4.0 technology to address quality and safety risks across various food sectors. We also discuss emerging trends, implementation challenges, and future research directions in this domain. The goal is to provide a clear comprehensive overview of how digital transformation is shaping safer and more resilient food supply chains around the globe [4, 5].

Food quality and safety risks in the agrifood supply chain are a critical global concern, especially with increasing complexity and connectivity. Key risks include microbiological and chemical contamination, food fraud, inadequate traceability, and logistics disruptions, all of which threaten public health, consumer trust, and economic stability. Managing these risks is a continuous process from farm to fork, requiring attention at every stage. On the farm, practices must prevent contamination, while processing plants need strict controls to eliminate hazards and prevent fraud. Maintaining appropriate conditions and traceability during distribution is crucial for preserving safety. Lastly, proper handling at retail and food service levels ensures safe meals for consumers. Each link in the supply chain is interdependent, making a farm-to-fork perspective essential for effective food safety management [4, 6, 7].

Industry 4.0 technologies enhance logistics, reduce waste, and support agro e-commerce, while the demand for safer, higher-quality food calls for an improved agro-food supply chain [8]. Preventing food fraud and ensuring traceability are crucial [9]. Digitalization, through farm management applications, improves food safety by reducing risks and enhancing transparency [10–12]. Traditional methods like HACCP and GMP remain essential but are increasingly supported by intelligent, data-driven systems that provide real-time monitoring and predictive insights. Addressing food safety and quality risks in the agrifood supply chain requires global collaboration, increased investment in digitalization, and a commitment to transparency and continuous improvement.

This systematic literature review evaluates the impact of Industry 4.0 technologies on managing food safety and quality risks in agrifood supply chains. Analyzing peer-reviewed studies from 2011 to 2023, it identifies these technologies' roles in addressing risks like microbial contamination, food fraud, and traceability. The study aims to help AFSC managers minimize quality issues and costly recalls. By addressing key research questions, it provides insights into I4.0 applications, identifies research gaps, and suggests directions to enhance the resilience and sustainability of global agrifood systems. Accordingly, the following research questions are posed:

- What Industry 4.0 Technologies are implemented for quality and safety Risk Management in AFSCs? (RQ1)
- What are the benefits and outcomes of I4.0 technologies in managing quality and safety risks in AFSCs? (RQ2)
- What are the main practical implications for industry stakeholders? (RQ3?)
- What research gaps and future trends are defined in literature? (RQ4)

The paper is organized as follows: Sect. 2 outlines the research methodology adopted. Section 3 discusses agrifood supply chain risks while Sect. 4 describes the Industry 4.0 technologies applied for risk management. Section 5 presents and discusses the results, and Sect. 6 concludes the review. A complete list of abbreviations for the reader's convenience.

2 Research Methodology

This research aims to provide insight into the digitalization-based support of agrifood products, addressing safety and quality concerns for agrifood supply chain risk managers. A systematic literature review (SLR) was conducted for this purpose. A systematic review is particularly valuable in a fast-evolving field like the application of Industry 4.0 technologies in agrifood supply chain risk management, where a variety of approaches, technologies, and theoretical frameworks often intersect. By mapping the current state of the literature, this study not only synthesizes existing knowledge but also highlights underexplored areas that merit further research.

It follows the classical four-step methodology, namely:

- Material collection: the literature is collected from various sources and is followed by screening according to selection criteria.
- Descriptive analysis: the extracted material is analyzed for the removal of duplicates.
- Material Selection: the articles to be reviewed are categorized according to the key technology.
- Material Evaluation: the reviewed material is critically and fully analyzed to identify the key insights, issues, trends, and opportunities and interpret results.

This method was chosen due to its widely recognized capacity to deliver a structured, transparent, and replicable approach to synthesizing existing knowledge, since it facilitates a comprehensive, theory-driven examination of major developments, recurring themes, methodological trends, and persistent gaps within the field.

To ensure methodological rigor and consistency, this study adopts principles adapted from the PRISMA framework (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [13]. PRISMA offers a well-established structure for systematically identifying, screening, and selecting studies based on clearly defined eligibility criteria. This approach helps minimize selection bias and enhances the credibility and reproducibility of the findings. The search process was guided by transparent inclusion and exclusion criteria, utilized a structured keyword strategy across multiple academic databases, and documented each step of the selection process in detail as is depicted in Fig. 1.

For this study, articles were retrieved from Scopus and Web of Science (WoS) over the course of January 2024. These platforms were chosen due to their extensive coverage of scholarly journals in operations management, industrial engineering, logistics, and information systems, which are the primary disciplines where research on Industry 4.0 and agrifood supply chain management is published. Keywords were

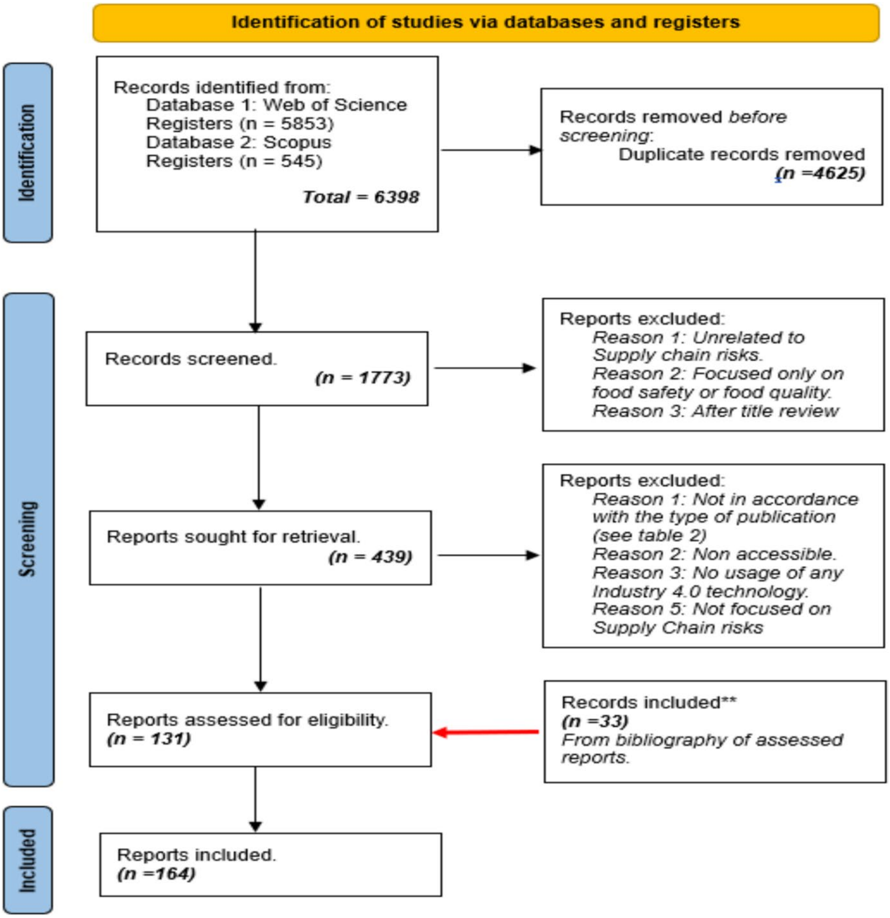

Fig. 1 Identification of selected articles to be included in the SLR [13]

searched in the title, keywords, and abstract of papers using a Boolean operator "OR" within groups and "AND" between groups. The list of keywords employed is provided in Table 1.

The search focused on English-language articles published from 2011 to 2023, aligning with Industry 4.0's introduction at the Hannover Fair. Once the search results were retrieved, duplicates were removed, and a title and abstract screening was conducted to ensure relevance. During the screening phase, the study used a set of specific inclusion and exclusion criteria, presented in Table 2, to make sure that the methods appeared and the results were relevant. The PRISMA framework and recommended practices for systematic literature reviews affected the choice of literature at the abstract and full-text review stages. After thorough screening, a total of 164 articles were selected for full-text analysis. This number reflects a carefully filtered sample aimed at ensuring both quality and thematic alignment.

Table 1 Structured keyword combinations for database search

Group A		Group B		Group C
Agr*food supply chain		Safety risk		Industry 4* OR I 4*
Agriculture supply chain	**AND**	Quality risk	**AND**	Digit*
Food supply chain		Safety disruption		Artificial intelligence OR AI
		Quality disruption		Additive manufacturing OR AM OR 3D printing
				Augmented reality OR AR, Virtual Reality OR VR, Mixed reality, OR MR
				Big Data OR BD
				Blockchain OR BC
				Cloud computing OR CC
				Cyber-Physical system OR CPS
				Digital Twins OR DT
				Information communication technology OR ICT
				Internet of Things OR IoT
				Machine Learning OR ML
				Robotic process automation OR RPA OR robot*
				Radiofreq* ident* OR RFID
				Quick response OR QR
				Barcode
				Sensor*
				GPS OR GIS
				Track Trace OR TT

3 Agrifood Supply Chain Quality and Safety Risks (AFSCRs)

The quality and safety of agrifood supply chains are increasingly critical due to their complex structures and vulnerability to biological, chemical, and operational risks arising from diverse biological, chemical, and environmental hazards, as well as operational and infrastructural challenges. For example, meat supply chains face risks such as microbial contamination, veterinary drug residues, and food adulteration [14, 15]. In contrast, dairy supply chains are particularly susceptible to spoilage and contamination due to their sensitivity to temperature fluctuations and variability in milk quality [16, 17]. The seafood sector experiences significant risks from inadequate production environments and poor sanitation of equipment [18]. Meanwhile, produced supply chains often struggle with microbial contamination resulting from irrigation and soil, as well as pesticide residues [19]. A taxonomy developed by Imbiri et al. [20] categorizes agribusiness risks into four types: natural, operational, market, and policy risks, while Ali et al. [21] also emphasize that supply chain disruptions, such as ineffective leadership and failures in IT systems, can increase food waste and inefficiencies. Mitigation strategies for these risks vary across sectors

Table 2 Inclusion and exclusion criteria with justification

Detail Information	Including	Excluding	Justification
Type of language	English	Other than English	Main understanding language
Keywords	Mentioned in Table 1	n.a	According to the paper's theme
Type of publications	Peer-reviewed journals	All types of thesis, Book chapters, whitepapers, conference proceedings/papers	The availability of a full thesis is not assured, white papers are not peer-reviewed, and their credibility is low. Conference papers and book chapters are not rigorously peer-reviewed, and the extension of these papers is observed in the articles so both may result in duplicity
Type of databases	Scopus and Web of Science (WoS)	Other than Scopus and WoS	Both have wide coverage and a reputation
Year of publication	2011 to 2023	Before 2011	The theme was not much developed before 2011, and little literature exists. The term Industry 4.0 was first established in 2011
Including areas	Agrifood supply chain and safety, quality risk and I4.0 technologies	Agile, Lean	According to the paper's theme

and countries, but they typically involve implementing control systems like Hazard Analysis Critical Control Point (HACCP), utilizing risk matrix tools, and adopting vertical and horizontal monitoring models [14, 19]. For small and medium-sized enterprises (SMEs) in the seafood industry, enhancing hygiene practices and maintaining equipment are crucial recommendations [18]. Additionally, emerging strategies such as blockchain technology and the Internet of Things (IoT) are increasingly being advocated to improve traceability and real-time monitoring [20]. Moreover, Moazzamet al. [16] suggest integrating risk indicators into performance frameworks, while Ummi et al. [22] propose using hybrid intelligent decision support systems (HIDSS) to manage reverse supply chain risks. Generally, risk factors have a significant influence on supply chain efficiency, costs, product quality, and stakeholder trust. For example, Nyamah et al. [23] found that demand volatility, unreliable supply, and environmental risks substantially impact performance metrics such as profitability and throughput, and Ali et al. [21] established a link between supply chain risks and increased food waste, highlighting the dual impact on sustainability and economic performance. Therefore, effective risk management is a critical issue for improving overall supply chain outcomes. In conclusion, research on agrifood supply chain risks has evolved from basic risk identification to the development of integrated risk management systems that leverage digital technologies. Effective risk management not only safeguards food safety and quality but also enhances operational performance and sustainability, but sector-specific highlights the necessity for tailored strategies.

4 Managing Quality and Safety Risks with Industry 4.0 Technologies in AFSCs

Industry 4.0 marks the fourth industrial revolution, fueled by advanced digital technologies that enhance automation, data exchange, and decision-making. Key technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data, blockchain, and cyber-physical systems (CPS) are transforming manufacturing, logistics, and supply chain management by improving efficiency and reducing costs. These innovations lead to smart factories, predictive maintenance, and enhanced supply chain transparency. While challenges like high implementation costs, data security, and workforce upskilling exist, the potential benefits of increased productivity and competitiveness make Industry 4.0 vital for modern industrial transformation. These technologies also help mitigate supply chain risks and improve resilience against uncertainties.

4.1 Additive Manufacturing or 3D Printing

3D printing, discussed since the 1980s, has only recently become affordable, enabling diverse materials and techniques across various sectors [24, 25]. Its advantages include integration with scanning, digital prototyping, and waste reduction, though its full potential remains untapped [26]. 3D food printing (3DFP) has gained attention for its benefits during COVID-19, supporting social distancing, minimizing food handling, and decentralizing production. It also promotes personalized nutrition and enhances food safety by reducing contamination risks [27]. Notable innovations include a 3D-printed biosensing device for detecting genetically modified maize (MON810) [28] and a portable biosensor for rapid *Escherichia coli* detection [29]. 3DFP enables on-demand food production, repurposes food waste into edible products, and offers sustainable solutions. However, challenges include inconsistent texture, taste, and repeatability, along with regulatory uncertainties regarding hygiene and long-term health impacts. The use of unconventional materials necessitates strict safety checks, limiting adoption. These issues keep 3D food printing in the developmental phase, requiring technological improvements and greater consumer acceptance [30].

4.2 Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL)

AI encompasses various computing systems, including machine learning (ML), deep learning (DL), natural language processing, and computer vision, allowing tasks generally associated with intelligence. ML, a subfield of AI, utilizes algorithms to learn from data for specific tasks. Advanced data analytic techniques (ADAT) enhance food safety and risk assessment by analyzing microbial genomic data, spectral imaging, and food processing data to identify risky patterns [31, 32]. AI improves food safety detection via direct (microbial) and indirect (supply chain) approaches, boosting predictive capabilities [33]. DL applications, such as predicting meat safety [34] and using image-based models for detecting tomato diseases [35], are noteworthy [36]. Some studies evaluate ML models for food and feed safety risk predictions using Rapid Alert System for Food and Feed (RASFF) data to optimize inspections and reduce contamination risks [37], while others use Bayesian networks to address gaps in predictions [38]. In unrelated sectors, decision trees and Naïve Bayes classify automotive suppliers based on resilience [39]. In agricultural contexts, a rice security risk assessment model integrating ML achieved 99.54% accuracy but was complex for non-experts [40], in wheat [41], while Iowa corn aflatoxin prediction achieved 96.77% accuracy but suggests dataset expansion for better risk sensitivity [42]. Retail food safety benefits from AI through improved compliance and monitoring [43], and the role of ML and crowdsourcing in detecting foodborne illness via Twitter is discussed, noting incomplete data limits broader predictions [44]. Ensemble learning enhances food inspections, improving detection accuracy [45], while an ML-based monitoring model for aflatoxin B1 contamination cut costs by 96% [46]. A hybrid model combining extreme learning machine (ELM) and mayfly algorithm (MA) addresses temperature control in cold chain logistics, minimizing spoilage risks [47]. AI modernizes food safety communication, improving public understanding [48]. Techniques like NLP, time-series forecasting, and reinforcement learning enhance food recall prediction [49]. Explainable AI (XAI) aids in fraud detection, ensuring transparency in supply chain risk [6], and visual analytics for food safety enhances regulatory decision-making [50]. ML analyzes climate change impacts on food safety, predicting microbial contamination with IoT integration for real-time monitoring [51, 52]. Lastly, AI adoption boosts sustainability in agrifood by optimizing yield and safety [53]. Overall integrating AI across the agrifood supply chain to enhance detection, transparency, and risk predictions [54, 55]. Challenges like big data and ML ethics are addressed in the P-SAFETY model [56], and ML's role in risk assessment and contamination detection raises concerns about accuracy and regulatory integration [57].

4.3 Augmented Reality (AR), Virtual Reality (VR)

Augmented reality (AR) systems support services like part selection in warehouses and mobile repair instructions. Virtual reality (VR) has been effective in virtual prototyping, machining, assembly, fault diagnosis, and various manufacturing operations. Key applications of VR and AR are in robotics, factory layout, and maintenance [58]. AR and VR help guide personnel intuitively, simplifying operation sequences and reducing human error. VR enhances product design through better visualization, while AR aids maintenance by enabling remote experts to generate instructions for on-site technicians [59].

4.4 Big Data (BD)

Big data in the agricultural chain can predict pathogens by linking environmental factors with hazards, addressing contamination risks, storage issues, and traceability gaps [60]. Food safety improves through smartphone hazard detection, climate data integration, and social media risk analysis. Public data assists in outbreak investigations and recalls [61]. A dynamic risk management system (DRMS) enables real-time *E. coli* hazard identification in leafy greens, revolutionizing microbial food safety through "precision food safety" [62, 63]. Whole genome sequencing (WGS) enhances outbreak detection [64, 65]. Big Data's impact on food safety includes addressing microbial contamination, sanitation, and traceability, enhancing HACCP through real-time sensor data. Predictive analytics, machine learning, and IoT improve monitoring, recall response, and decision-making while facing challenges of data privacy and integration [66]. Crowdsourcing from consumer reports supports contamination and allergen management [67]. Platforms like "IWasPoisoned.com" aid outbreak detection but face data verification issues. Big data integrates regulatory, processing, and consumer feedback into an early warning system (FSEWS) for better risk identification despite system fragmentation [68]. Web monitoring analyzes food safety discourse, revealing risks but hindered by misinformation [69]. Big data also addresses marine biotoxins like Ciguatera fish poisoning (CFP) amid challenges like data fragmentation [70]. Additionally, decision support systems (DSS) enhance risk management and require investment in expertise [71]. Interactive simulation models like SIMIO assess supply chain disruptions, improving resilience while facing challenges in scaling and real-time integration [72].

4.5 Blockchain (BC)

Blockchain is a distributed database that operates through multiple independent nodes, serving as a decentralized ledger for secure and credible information recording. It facilitates efficient point-to-point transactions using encryption, timestamps, consensus, and reward mechanisms, addressing issues of reliability, security, cost, and efficiency in centralized storage. The increasing concerns over food safety have amplified the need for enhanced traceability in the supply chain, which blockchain technology addresses by ensuring payment security and transparency about product origins, certifications, and contamination risks [73]. The integration of blockchain in food safety is becoming a trend. In October 2016, IBM, Wal-Mart, and Tsinghua University launched a blockchain-based food traceability pilot in China. Similarly, in March 2017, Alibaba and PricewaterhouseCoopers initiated a food supply blockchain test project. Since September 2019, Walmart has mandated its vegetable suppliers to utilize IBM's blockchain for real-time tracking. These initiatives demonstrate a collaborative approach to food safety among stakeholders in the global supply chain [74]. Blockchain technology offers a new method for ensuring data authenticity in food traceability, benefiting all parties, including producers, processors, retailers, and consumers. Researchers have developed various blockchain-based systems to improve data collection and monitoring [75], enhance transparency in agri-insurance [76], automate risk assessment for rice supply chains automating shelf life [77, 78], and track food from farm to table [79, 80]. Traditional methods rely on manual record-keeping, while blockchain automates data collection, improving fraud prevention and traceability [81]. Numerous studies highlight blockchain's potential in enhancing food safety across various sectors, including plants, animals, and processed foods, confirming its potential to prevent fraud and enhance consumer trust [82], as well as the importance of addressing barriers to adoption such as costs and regulations [83, 84].Blockchain enhances traceability in various sectors, including dairy [85], seafood [86], wine [87], coffee [88], bakery [89], and grains [90]. Integrating IoT and smart contracts with blockchain can further strengthen food safety monitoring and compliance automation, though high implementation costs and interoperability remain challenges [91, 92]. Future research should focus on scalability and regulatory frameworks to optimize blockchain for food safety solutions.

4.6 Cloud Computing (CC)/Cyber Physical Systems (CPS)/Information Communication Technology (ICT)

Ensuring safe farming practices is essential for food supply chain traceability, with reasonable pesticide use being crucial for food safety and sustainable production. Food safety and cleaner production have gained significance in supply chains, and effective pesticide control supports these goals. A cloud-based platform for rational pesticide use, described in [7], includes a pesticide use control cloud platform (PUCC) and a pesticide user application (PUA) that guide users through pesticide purchasing, application, harvest timing, and evaluation. The article highlights quality risks such as excessive pesticide residues, inadequate application methods, and counterfeit pesticides, as well as safety risks like chemical contamination and environmental impact. Advantages for farmers include reduced unreasonable usage and improved vegetable quality, while disadvantages involve increased costs and reduced efficiency. The system enhances both internal and external traceability for crop quality and safety [7]. ICT technologies in agriculture boost efficiency and production quality, providing added value to the food supply chain. As farmers seek innovative solutions, the next step involves integrating these systems into cyber-physical production systems with smart devices via the Internet of Things, mapping the entire process electronically, which could significantly enhance efficiency and quality [93].

4.7 Digital Twins (DT)

Digital twin (DT) technology, a key component of Industry 4.0, traces its origins to NASA's Apollo 13 program, where physical replicas enabled real-time simulation and problem-solving [94]. Bhandal et al. [95] define DT as a virtual replica of real-world operations, connected through sensor data and big data analytics. They highlight their role in enhancing supply chain resilience, risk management, efficiency, and sustainability. Ivanov et al. [96, 97] emphasize DT's ability to dynamically match supply chain designs to disruption patterns. Through real-time data from IoT sensors, track-and-trace systems, and online risk databases, DTs identify critical hotspots and provide alerts. Integrated with simulation models and machine learning, they facilitate disruption identification, modeling, and impact assessment [98]. Shrivastava et al. [99] applied DT to perishable supply chains, simulating temperature and humidity effects on strawberries across 21 packaging types. Their DT model addressed quality risks like freshness loss, condensation, and poor packaging design, as well as safety risks such as microbial contamination and inadequate temperature control. By predicting shelf-life metrics and optimizing packaging, DTs significantly reduce experimental trials, enabling efficient, data-driven improvements.

4.8 Internet of Things (IoT)

The Internet of Things (IoT) refers to a network of physical objects, like home appliances, vehicles, and medical devices that communicate without human intervention. This technology connects billions of smart devices, allowing data exchange and transforming various sectors, such as industrial automation, healthcare, smart cities, and agriculture. In agriculture, IoT enhances productivity through advanced sensors that monitor soil moisture, plant hydration (leaf moisture), atmospheric conditions, sunlight exposure, and rainfall predictions. These tools are mainly used in greenhouses, optimizing irrigation, climate control, and crop health, facilitating real-time monitoring, storage in cloud, and data-driven decisions, which ultimately improve efficiency, reduce waste, and increase yield [100–102]. Companies like See Your Box Ltd (SYB) offer Industrial IoT solutions for real-time monitoring in logistics, enhancing safety and traceability [103]. IoT technologies, including RFID, help mitigate risks in supply chains, such as temperature instability and counterfeit products, improving quality and reducing costs [104, 105]. These innovations also improve food supply chain traceability, allowing faster recalls and compliance with regulations [106]. Examples include Xsense® for monitoring fresh produce and IoT Risk Management Systems for cold chain logistics, which manage spoilage and contamination risks [107–109]. Additionally, traceability platforms like IPTPSCP for Chinese tea combat adulteration and counterfeit products, improving monitoring efficiency [110]. IoT-based solutions address quality risks in grain and fruit supply chains, enhancing food safety and sustainability [111–116]. IoT-enabled sensors improve traceability and quality control in food supply chains, enhancing sustainability and economic performance. For example, Mishra et al. [117] focused on drying processes for leafy vegetables, mitigating nutritional degradation and microbial risks through automated IoT controls and Ataei Kachouei et al. [118] discussed IoT sensors for detecting food toxins and pathogens, supporting precision agriculture and food safety, but noted challenges in cost and scalability. Analyzing high-risk food supply chains, identifying contamination risks and logistics inefficiencies, while IoT RFID tags and Big Data Analytics enhanced traceability and safety compliance [100]. Implemented case studies of IoT in agrifood supply chains consist of the development of a Smart IT-Based Traceability System for Indonesia's rice supply chain, addressing chemical contamination and inefficiencies with QR codes and business intelligence tools [119] applications to strawberry logistics, achieving 97.5% accuracy in risk prediction by identifying temperature issues and pathogen growth [120] and optimization of e-commerce fresh supply chains using Big Data and IoT for improved storage and traceability [121]. Finally, Zheng et al. [122] introduced a food safety traceability system with RFID, IoT, and QR codes to enhance contamination detection and recall efficiency.

4.9 Robotics (Rbs)

The application of robotic technology in the food industry, including manufacturing, handling, processing, and serving, remains underexplored in the literature. Robots, which are automated mechanical manipulators controlled by computers, play a crucial role in enhancing accuracy, efficiency, and reliability in various industries [123, 124]. In agriculture and food production, robots are utilized for tasks such as seeding, harvesting, processing, and packaging. They also play a role in quality detection for bakery and meat products and automate processes in the beverage industry, such as cleaning, counting, and filling bottles [125]. Additionally, robot learning technology employs high-definition cameras for defect identification and inspection, improving sanitation and minimizing cross-contamination risks [126]. Micro-unmanned aerial vehicles (μUAV) with multi-spectrum cameras are used in agriculture for aerial surveys to assess forest areas and crop biomass [127]. However, the food industry remains a relatively new market for robots, facing challenges in hygiene standards during direct food contact [128]. Various robotic systems, including pick-and-place, packaging, and inspection robots, help enhance operational efficiency, reduce errors, and address hygiene issues caused by manual handling.

Moreover, robots are classified based on their applications, such as food handling, packaging, and serving [129].

4.10 Track and Trace (Global Positioning System, GPS; Geographical Information System, GIS)

The study of LeBlanc et al. [130] examines the Canadian food distribution system for ready-to-eat (RTE) lettuce, focusing on quality and safety risks. Quality concerns include temperature control, prolonged storage, and logistical inefficiencies, while safety risks involve *E. coli* O157:H7 contamination, cross-contamination, and limited traceability. The study highlights Industry 4.0 technologies, particularly the CanGRASP tool, which integrates GIS mapping and simulation tools to predict contamination and improve outbreak response. Findings suggest that this approach strengthens food safety risk assessment and emergency preparedness. Zhang et al. [131] introduced APT3, an event-driven traceability system for harvesting wheat using GPS data to create automated traceability trees. The system addressed quality risks such as inadequate traceability, manual data recording errors, and difficulty visualizing transfer events. Safety risks included delayed responses to food contamination and failure to isolate defective batches, increasing recall costs. The system enhanced traceability, reduced labor, and optimized supply chain operations. These technologies improve logistics transparency, aiding rapid recalls and preventing intentional contamination such as bioterrorism [132]. GIS further supports risk assessment by integrating environmental and health data. Moriarity et al. [133] used GIS to analyze mercury contamination in fish, revealing quality risks like inconsistent pollutant monitoring and safety risks of increased human exposure in hydroelectric and mining regions.

4.11 Integrated Industry 4.0 Technologies

The safety of food products is a major concern for consumers, government agencies, and the food industry, especially with the complexities introduced by global food production. Traditional methods for ensuring food safety, such as manual tracking and paper documentation, have proven inadequate in precision and efficacy [79]. Many articles in this subsection focus on the implementation of three or more Industry 4.0 technologies. One study on perishable agricultural supply chains highlights post-harvest losses and handling inefficiencies as key risks, with cyber-physical systems (CPS) and IoT enhancing traceability and reducing losses through real-time monitoring [134]. Another research emphasizes digital transformation in food manufacturing, addressing inconsistent quality and contamination due to poor monitoring. Industry 4.0 solutions like cyber-physical production systems (CPPS), Industrial Internet of Things (IIoT), and big data improve efficiency but face cost and infrastructure challenges [135, 136]. A study on supply chain risk management identifies supply–demand variability and traceability gaps as quality risks, while natural disasters and cybersecurity threats pose safety risks, with technologies like big data analytics and blockchain aiding risk mitigation [137, 138]. Digitalization in food value chains highlights real-time monitoring and transparency challenges, with safety risks from contamination and non-compliance. Technologies such as IoT and AI improve risk management, but interoperability issues persist [139, 140]. Research on traceability in live animal products notes quality risks from data loss and inconsistent identification, while safety risks include delayed outbreak detection. Blockchain and IoT enhance compliance but face adoption challenges [141, 142]. A study on the agrifood supply chain points to farming yield variability and regulatory gaps as quality risks, with IoT and RFID improving transparency and efficiency despite the need for better adoption policies [143, 144]. Further research details challenges in the meat cold chain logistics, citing spoilage and pathogen contamination as risks, with IoT and blockchain aiding transparency but facing cost issues [145]. Studies on blockchain in food safety highlight contamination risks and ineffective recall systems, while AI and big data address inefficiencies but highlight cybersecurity needs [146]. Research on digital transformation in the agrifood supply chain highlights traceability gaps and real-time monitoring challenges as quality risks, while contamination, ineffective recalls, and counterfeit risks pose safety threats. IoT, blockchain, AI, and big data improve efficiency and sustainability, but further research is needed to enhance integration and consumer trust. Finally, regarding supply chain resilience, operational inefficiencies and safety risks are identified from geopolitical disruptions, with IoT and AI enhancing resilience [144, 147–149].

5 Results and Discussion

The total number of articles retrieved after the methodology as stated in Sect. 2 was 164 articles and of several publication years. The results are shown in Fig. 2, where it is evident that the COVID-19 pandemia has triggered the interest of the scientific community in managing quality and safety risks through the use of I4.0 technologies in the agrifood supply chains, as also stated by Galanakis et al. [150].

5.1 Comparison of Industry 4.0 Technologies for Quality and Safety Risk Management in AFSCs (RQ1)

Industry 4.0 (I4.0) technologies have been widely adopted to tackle the multifaceted quality and safety risks present in AFSCs. From the total of 164 reviewed articles, 155 explicitly describe the application of one or more I4.0 technologies, confirming the increasing integration of digital tools in this domain. The remaining nine articles examined supply chain risks more generally but did not detail any specific I4.0 technology; these studies were instead classified by industry type to contextualize their findings (Table 3).

Among the technologies discussed, blockchain stands out as the most frequently addressed, appearing in 51 articles. This highlights its strong perceived potential to enhance traceability, transparency, and trust throughout the supply chain. Artificial intelligence (AI) follows with 23 articles, demonstrating its relevance in predictive analytics, automation, and intelligent decision-making. The Internet of Things (IoT)

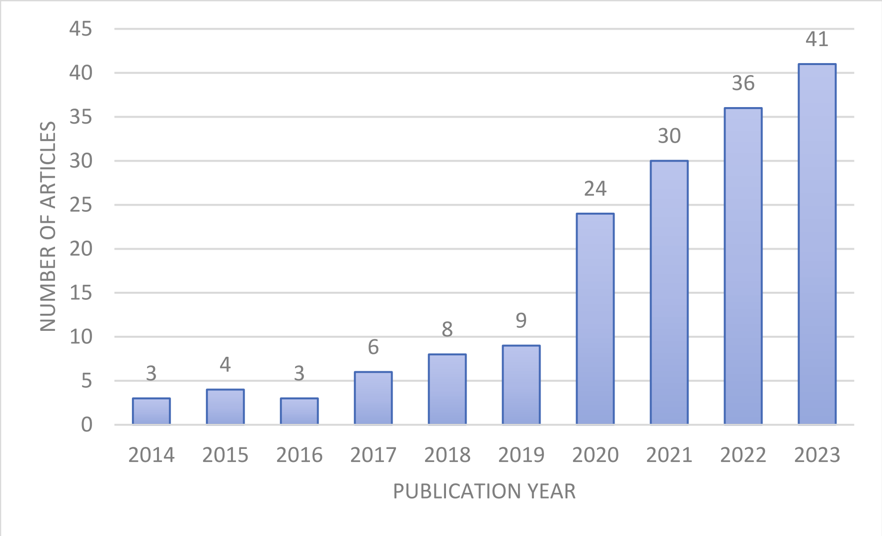

Fig. 2 Articles per publication year included in SLR

appears in 22 articles, showcasing its importance for real-time monitoring and data collection along production and distribution stages.

In addition, the reviewed articles were grouped into thematic clusters based on their main focus areas (Table 4). The largest share falls within the data-driven cluster (34 articles), highlighting the central role of data generation, sharing, and analysis for all AFSC stakeholders. Other clusters include those concentrating on technologies for traceability, automation, and predictive control, illustrating the diverse ways I4.0 is leveraged to manage safety and quality risks.

The first cluster includes data-driven technologies like artificial intelligence (AI), machine learning (ML), and big data which play a pivotal role in predictive risk identification. The agrifood sector has seen an explosion of data in recent years—from sensor readings and farm equipment to lab test results, retail sales, and even social media feedback on food products. Big data analytics refers to the capability to collect and analyze these massive, diverse datasets, while artificial intelligence (AI) (including machine learning and deep learning techniques) provides advanced methods to detect patterns and make predictions from the data. They enable a shift from reactive quality control to proactive and predictive risk management [1]. Of the major applications of these data-driven technologies, the focus lies in predicting contamination and spoilage risks before they occur. In the study of Donaghy et al. [1], the potential of feeding big data from "precision agriculture, connected factories, logistics, and even public health databases" into dynamic risk models for food safety is explored. These models, powered by AI, could improve the dynamism of microbial risk management, identifying emerging hazards in real time and aiding decisions like halting distribution of a suspect batch. In general, AI and big data are increasingly seen as essential for implementing preventive controls and hazard analysis and critical control point (HACCP) plans with greater precision and real-time

Table 3 Total number of retrieved articles according to Industry Type and I4.0 technologies assessed

Industry type	Artificial intelligence (AI) (ML/DL/SIMULAT.)	Additive manufacturing (AM or 3D)	Blockchain	Big data	CC/CPS/ICT	Digital twin	Internet of Things (identifiers, sensors)	Robotics & automation	Track trace (GPS/GIS)	I4.0 technologies combined (> 3)	Risk identification/none I4.0 used	***Sum***	%
Bakery pasta			1							1		***2***	***1.22***
Coffee/tea			3				1					***4***	***2.44***
Dairy products			3		1						1	***5***	***3.05***
Eggs			1									***1***	***0.61***
Fresh/raw products	3		7	1	2		5			5	3	***26***	***15.85***
Fruits			2			1	3					***6***	***3.66***
Grains/rice	5		4		1		3		1	2		***16***	***9.76***
Meat products			4				1			2	2	***9***	***5.49***
Not determined	12	2	16	5		2	4	1		19	1	***62***	***37.80***
Perishable processed products	3	1	6				3		1	5	1	***20***	***12.20***
Sea food			3	1					1	1	1	***7***	***4.27***
Vegetable					1		1			2		***4***	***2.44***
Winery			1				1					***2***	***1.22***
Sum	***23 (14.02%)***	***3 (1.83%)***	***51 (31.10%)***	***7 (4.27%)***	***5 (3.05%)***	***3 (1.83%)***	***22 (13.41%)***	***1 (0.61%)***	***3 (1.83%)***	***37 (22.56%)***	***9 (5.49%)***	***164***	

Table 4 Clusters of I4.0 technologies and their included technologies according to their focus

Clusters of I4.0 technologies	Included technologies	Number of articles	%
Data-driven technologies	Artificial intelligence, machine learning and big data	34	21.94%
Traceability/transparency technologies	Blockchain	29	18.71%
Traceability & sensor and monitor technologies	Blockchain and IoT technologies	28	18.06%
Virtualization & sensor and monitor technologies	Internet of Things (IoT)	19	12.26%
Digital twins	Digital twins (DT)	3	1.94%
Cloud computing, data platforms	Cloud computing (CC, ICT)	3	1.94%
Additive manufacturing (AM)	Additive manufacturing (3D printing)	3	1.94%
Cyber physical systems	Cyber physical systems (CPS)	2	1.29%
Robotic automation & precision technologies	Robotics	1	0.65%
Integrated I4.0 technologies	*More than 3 technologies analyzed*	33	21.29%
Total sum	***Total sum***	***155***	***(100%)***

oversight. Such an approach moves food safety towards a risk-based, data-driven paradigm rather than periodic spot-checks. Another application of AI is its use for automated quality inspection—for example, scanning produce for defects or even detecting foreign objects and preventing packaging errors or mislabeling of products. These AI-driven inspection systems can sort out substandard products faster and more consistently than manual inspection, improving overall quality [2, 3]. Moreover, these technologies help optimize logistics to maintain quality. By analyzing large datasets on transportation routes, weather, and past delivery performance, ML algorithms can recommend optimal shipping methods or re-routing to minimize transit time for perishable goods. Furthermore, machine learning models are being used to forecast shelf life more accurately. Rather than relying on static expiration dates, these models incorporate data like real-time temperature exposure and product-specific kinetics to predict when an item will likely become unsafe or poor quality. This can drive smarter stock rotation and markdown decisions, again cutting down waste.

In contrast, the second cluster consists of traceability and transparency technologies which focus on record-keeping and information flow to manage quality/safety risks. *Blockchain* is prominent here: by creating tamper-proof, distributed ledgers, blockchain improves the credibility of traceability systems and the integrity of the supply chain. It ensures that key data (origins, certifications, processing steps) cannot be altered, thereby quickly pinpointing contamination sources and preventing data fraud. This I4.0 technology directly addresses traceability gaps by making it possible to trace any food item's history quickly and with confidence, thus minimizing public health impacts as outbreaks can be traced in seconds rather than in days. Blockchain's data integrity is especially useful for combating food fraud and ensuring authenticity. Because entries on a blockchain ledger cannot be altered unnoticed, it becomes extremely difficult for unscrupulous actors to tamper with records. Beyond traceability and fraud, blockchain can help with compliance and sustainability tracking. It can record if a food item meets organic standards, halal certification, or carbon footprint targets, and these records are readily accessible and trustworthy for auditors or consumers [151]. Track-and-trace tools (e.g., GPS and GIS mapping) complement blockchain by automatically capturing product movements and environmental conditions. They have been used for commodities like wheat, eliminating manual recording errors and enabling clear visualization of a product's journey. This not only helps contain food safety incidents by quickly tracing back to contamination points but also improves operational efficiency.

A limitation, however, is that blockchain alone does not validate the quality of the data entered and works best when coupled with sensors or diagnostics (to input reliable data) and when widely adopted by all supply chain partners. The combination of BC and IoT is validated by the augmented number of articles combining these technologies. As a result, the third cluster of 28 articles combines the traceability of *blockchain* and the sensor/monitoring techniques of *IoT technology*. IoT sensors can automatically feed data (e.g., temperature readings, timestamps) into a blockchain, creating a trusted log of conditions that a food product has experienced. The study of Derakhti et al. [2] combined IoT sensors with blockchain to create a farm-to-consumer traceability system that improves product quality transparency.

The *Internet of Things (IoT)*—networks of connected sensors and devices—is a cornerstone of Agrifood 4.0 and consists of the fourth cluster. IoT devices enable continuous, real-time monitoring of environmental conditions and product status throughout the supply chain, forming the backbone of real-time risk management. This real-time visibility is critical for preventing contamination and spoilage. A recent case study of Gillespie et al. [152] deployed a real-time IoT anomaly detection system in refrigerated delivery trucks for meat, fruits, and vegetables. The IoT sensors detected refrigeration failures and notified drivers/warehouse staff immediately, preventing food spoilage and waste that would occur with undetected temperature abuse. By continuously logging conditions, such systems also produce traceable records to verify that foods were kept within safe thresholds (a compliance requirement for cold chains. IoT sensors are used on farms and in processing facilities to detect hazards and ensure quality. For instance, smart sensors in a dairy plant can monitor milk temperature and pH in real time, giving an early warning of potential bacterial growth before the product spoils. In grain storage, IoT devices track moisture levels in silos to prevent mold contamination. IoT-based surveillance of water quality and feed in aquaculture or livestock farming helps mitigate contamination at the source [153]. Another critical contribution of IoT is enhanced traceability. By tagging products or batches with IoT devices (like RFID tags, QR codes, or wireless sensors), companies can automatically capture data on origin, processing, and handling at every node. This continuous tracking builds a rich traceability record. In the event of a contamination incident or quality issue, IoT-enabled traceability allows rapid identification of the affected lots and their movement. Overall, IoT underpins many other Industry 4.0 solutions by supplying the real-time, high-volume data needed for intelligent decision-making [5].

A more recent innovation is the concept of *digital twins*, which consists of the fifth cluster. A digital twin is a virtual model of a physical object or process that runs in parallel, replicating the state of the real system in real time and enabling simulation of future states. In the food sector, digital twins are being explored for both processing operations and entire supply chains. For instance, a "digital food twin" of a processing line might incorporate real sensor inputs (temperatures, machine speeds, product properties) into a simulation model that can predict how the food will turn out under current settings. An extended digital twin of a supply chain could allow companies to test "what-if" scenarios in the virtual model and see the impact on product safety and quality, thereby improving contingency planning. Such simulation capability is valuable for risk assessment to identify vulnerabilities and optimal interventions without endangering real products [151]. The digital twin concept ties together various technologies (IoT, AI, blockchain, etc.) into integrated solutions that monitor and adjust food processes in real time, while keeping detailed records. By doing so, they can greatly improve supply chain resilience (ability to adapt to changes) and quality consistency. If a problem is detected in the virtual model, the real system can be alerted immediately—preventing minor issues from snowballing into major quality or safety failures. However, digital twin technology is still in early stages in agrifood; it requires high data fidelity and interdisciplinary models (combining microbiology, physics, supply chain logistics) to be effective. Not all companies have the resources or expertise to develop such complex models, and standard methods for building food supply chain twins are lacking.

Cloud computing is the backbone of many of the I4.0 technologies as it provides scalable storage and processing power, enabling even small food producers or processors to partake in sophisticated digital systems without massive on-premises IT investments. In an agrifood supply chain context, cloud-based platforms serve as shared information hubs where data from farms, sensors, processing plants, distribution centers, and retail can be aggregated in real time. Cloud platforms support real-time dashboards and decision support systems that managers can use to oversee quality and safety. By gathering data, the cloud makes it easier to implement advanced analytics (like big data algorithms that need large datasets) and to share traceability information with consumers. Therefore, cloud computing underpins many of the industry 4.0 applications in agrifood by providing infrastructure for integration, allowing technologies like IoT, AI, and blockchain to work in concert on a global scale [2].

Additive manufacturing (3D printing) is another emerging tool—its use in food is limited but growing, particularly for creating 3D food designs or prototypes. While not yet mainstream for risk management, 3D food printing during the COVID-19 pandemic was noted to reduce human contact in food preparation, thus lowering contamination opportunities. It also allows rapid prototyping of packaging or equipment parts, potentially improving design safety by testing multiple iterations quickly. However, current research indicates that the full potential of 3D printing in agrifood (for example, printing biosensors or custom sanitary tools) has yet to be realized, marking it as a technology to watch rather than one broadly deployed in practice [26, 27, 30].

Robotics and automation are transforming how food is produced, processed, and handled, bringing both efficiency gains and food safety benefits. In many agrifood sectors, robots now perform tasks that were traditionally done manually, ranging from planting and harvesting in the field to sorting, cutting, and packaging in factories. By reducing human contact with food and standardizing operations, robotics can markedly lower the risk of contamination and improve consistency in quality. Dairy farms and meat processing are industrial examples [154]. In summary, robotics and automation contribute to safer and higher-quality food production by minimizing human error, ensuring more sterile handling, and maintaining consistent processing conditions. Future developments in this area are expected to further improve occupational safety (fewer worker injuries) and food hygiene, although integration and cost remain considerations. The benefits are clear in terms of consistency and throughput—robots do not tire or deviate from specified processes—and they also protect worker safety by taking on dangerous tasks (e.g., working in extreme cold storage environments). Nonetheless, the food industry has been slower than other sectors to adopt robotics, mainly due to stringent hygienic design requirements and the difficulty of handling unstandardized food items. Any robot directly contacting food must be easily cleanable to food-grade standards, which raises costs and engineering complexity. This challenge, alongside integration costs, means robotics are currently used predominantly in structured environments (like processing packaged foods) rather than for delicate tasks (e.g., picking soft fruits) where human dexterity is still hard to replicate [115]. *CPS* (the integration of sensor networks with automated control and decision systems) is shown to improve on-farm practices and food manufacturing by reducing human error and maintaining optimal conditions. CPS in agrifood extends from farm production into manufacturing and distribution—essentially forming a “smart supply chain” where each physical step has a digital shadow or control point. Research indicates CPS implementations can enhance traceability and responsiveness [2].

In the last cluster identified, a notable trend is the broadening of focus from individual technologies to integrated systems. Early studies often examined one technology in isolation (e.g., using RFID for traceability, or applying data mining to detect fraud patterns). More recent literature emphasizes combining tools into holistic solutions—for instance, IoT + blockchain for traceability, or AI + robotics for automated quality control.

Table 5 presents the distribution of the articles over the review period 2011–2023. The data reveals a notable upward trend in research output, indicating growing academic and industry interest in the integration of I4.0 technologies to strengthen safety and quality risk management in AFSCs. This trend reflects a broader shift toward digital transformation aimed at making food supply chains more resilient, efficient, and transparent. As indicated in Table 5, after the spread of COVID-19, there is an elevated interest in integrating I4.0 technologies in managing quality and safety risks in AFSCs. In summary, the technologies most studied—IoT, blockchain, big data/AI, CPS/automation—collectively shape an integrated risk management framework. IoT provides real-time data, blockchain provides secure data sharing, analytics/AI provide intelligence to interpret data and predict issues, and automation/CPS provide the means to act on data (whether alerting humans or adjusting

Table 5 Clusters of I4.0 technologies and their included technologies per year of publication

No	Cluster of I4.0 technologies	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	*Total sum*	%
1	Data-driven technologies			2	2	2	1	3	6	9	9	***34***	21.94%
2	Traceability & transparency technologies	1					1	9	2	6	10	***29***	18.71%
3	Traceability & sensor/monitor technologies						3	8	5	5	7	***28***	18.06%
4	Virtualization & sensor/monitor technologies	2	2	1		1	2		5	3	3	***19***	12.26%
5	Digital twins								1	1	1	***3***	1.94%
6	Cloud computing, data platforms					1				2		***3***	1.94%
7	Additive manufacturing								2	1		***3***	1.94%
8	Cyber physical systems				2							***2***	1.29%
8	Robotic automation & precision technologies					1						***1***	0.65%
9	*Integrated I4.0 technologies*		*1*			*1*	*1*	*3*	*8*	*9*	*10*	**33**	21.29%
	Total Sum	***3 (1.94%)***	***3 (1.94%)***	***3 ((1.94%)***	***4 (2.58%)***	***6 (3.87%)***	***8 (5.16%)***	***23 (14.84%)***	***29 (18.71%***	***36 (23.23%)***	***40 (25.81%)***	***155***	***100%***

processes automatically). The literature consistently shows that deploying these technologies correlates with an improved ability to prevent, detect, and respond to quality and safety risks.

Finally, it is interesting to analyze the application of I4.0 technologies across AFSCs. Regarding the sectors covered, most practical implementations were found in fresh/raw products and perishable processed goods. These sectors face higher quality and safety risks due to their perishability and stricter handling requirements. Notably, a considerable portion of the articles addressed I4.0 technologies in a cross-sectoral manner without specifying a distinct industry type, emphasizing the general applicability of digital solutions. Table 6 categorizes 155 articles on I4.0 technologies by agrifood product type, revealing that most studies focus on implementations in fresh/raw products and perishable processed goods. However, 61 articles address I4.0 technologies broadly, without specifying a product type, suggesting a need for broader, large-scale industry applications across diverse AFSCs.

5.2 Benefits and Outcomes of I4.0 Technologies in Managing Quality and Safety Risks in AFSCs (RQ2)

Our research is identifying specific benefits and outcomes of I4.0 technologies regarding quality and safety risks, as described in Table 7. Commonly reported outcomes include improved response time to safety issues (due to real-time monitoring and traceability) [1, 155], reductions in food waste and losses promoting sustainability [5, 156, 157], better product consistency (through process automation and data-driven control), and enhanced trust among supply chain partners and with consumers [151, 158–160]. Increased consumer trust is another key benefit identified [161–163]. There is also attention to social and economic impacts—for instance, how automation might affect the labor force in food industries, or how small farmers can be included in digital supply chains [164, 165].

5.3 Practical Implications for Industry Stakeholders (RQ3)

For agrifood businesses and supply chain participants, the findings suggest that embracing Industry 4.0 is increasingly becoming a necessity rather than a luxury when dealing with quality and safety risk management.

Food producers and processors can derive immediate benefits from technologies like IoT sensors and robotics to ensure consistent product quality and reduce contamination in their facilities. For example, installing environmental sensors in storage units or along production lines can alert managers to unsafe conditions (temperature, humidity, etc.) instantly, preventing spoilage or bacterial growth before it affects large batches. Such interventions can save companies significant costs by cutting down waste and avoiding expensive recalls, as evidenced by case studies where real-time monitoring led to double-digit percentage reductions in product loss and quality-related returns.

Supply chain logisticians and distributors can gain from improved traceability and inventory visibility. By integrating GPS/GIS tracking and blockchain ledgers,

Table 6 Total number of retrieved articles per industry type and I4.0 technologies clusters assessed

Industry type/I4.0 cluster	Additive manufacturing	Cloud computing, data platforms	Cyber physical systems	Data-driven technologies	Digital twins	Integrated I4.0 technologies	Robotic automation & precision technologies	Traceability & sensor technologies	Traceability & transparency technologies	Virtualization & sensor technologies	*Sum*	%
Bakery pasta						1		1			***2***	***1.29***
Coffee/tea								2	1	1	***4***	***2.58***
Dairy products		1						2	1		***4***	***2.58***
Eggs								1			***1***	***0.65***
Fresh/raw products			2	5		4		2	5	5	***23***	***14.84***
Fruits				1	1			1	1	2	***6***	***3.87***
Grains/rice		1		5		2		1	4	3	***16***	***10.32***
Meat products						2		1	3	1	***7***	***4.52***
Not determined	2			18	2	17	1	11	7	3	***61***	***39.35***
Perishable processed products	1			4		4		4	4	2	***19***	***12.26***
Sea food				1		1		2	2		***6***	***3.87***
Vegetable		1				2				1	***4***	***2.58***
Winery									1	1	***2***	***1.29***
Sum	***3 (1.94%)***	***3 (1.94%)***	***2 (1.29%)***	***34 (21.94%)***	***3 (1.94%)***	***33 (21.29%)***	***1 (0.65%)***	***28 (18.06%)***	***29 (18.71%)***	***19 (12.26%)***	***155***	

Table 7 Summary of key benefits of I4.0 technologies in managing safety and quality risks in AFSCs

Improved food safety & quality control	Real-time monitoring: IoT sensors track temperature, humidity, and contamination risks in food storage and transport
	Early risk detection: AI and big data enable predictive risk analysis for food contamination and fraud detection
	Traceability & transparency: Blockchain ensures secure, tamper-proof traceability from farm to table, reducing fraud
Enhanced supply chain efficiency & resilience	Automation & robotics: Smart manufacturing reduces human error, increases productivity, and ensures consistent quality
	Supply chain optimization: AI-driven predictive analytics optimize logistics, reduce delays, and minimize food waste
	Blockchain for supply chain security: Enhances food traceability, reduces fraud, and strengthens consumer trust
Sustainability & waste reduction	Reduced food waste: Smart logistics and monitoring minimize spoilage in perishable goods
	Energy efficiency: IoT-based cold chain management reduces energy consumption and enhances sustainability
	Digital twins: Simulations optimize packaging and processing, extending shelf life and reducing food loss
Cost savings & risk mitigation	Automated quality inspections: AI-powered systems reduce manual inspection costs while improving accuracy
	Lower compliance costs: Digital compliance tracking streamlines regulatory reporting and reduces penalties
	Resilience against disruptions: Industry 4.0 helps mitigate risks from supply chain disruptions (e.g., pandemics, cyber threats)
Data-driven decision-making	Big data analytics: Improves trend analysis, demand forecasting, and real-time risk assessment
	AI-driven insights: Machine learning models predict food safety risks, enhancing proactive decision-making
	Crowdsourced data: Consumer feedback and social media analysis improve food safety monitoring
Consumer trust & regulatory compliance	Improved transparency: Digital records and blockchain increase consumer confidence in food safety claims
	Compliance with food safety standards: Automated tracking ensures adherence to global regulations (e.g., HACCP, FSMA)
	Enhanced fraud prevention: Traceability reduces counterfeiting and mislabeling risks

they can rapidly trace shipments, authenticate product origins (important for verifying organic or Halal products), and isolate any compromised goods with minimal disruption to the rest of the supply chain. This not only mitigates the impact of safety incidents but also boosts efficiency—for instance, automated traceability systems eliminate manual record-keeping, freeing up labor and reducing errors.

Retailers and food service companies can embrace these technologies to reinforce consumer confidence. With greater transparency (such as scanning a QR code that reveals a product's farm, processing dates, and safety certifications stored on a blockchain), consumers gain trust in the authenticity and safety of what they purchase. In an age of elevated consumer awareness, this trust can translate to brand loyalty and market advantage. Furthermore, digital technologies facilitate compliance with food safety regulations. They provide auditable data for inspectors and certifications (e.g., automated temperature logs for refrigerated transport, or blockchain records for traceability audits), thus reducing the burden of paperwork and the risk of non-compliance penalties.

For regulators and public health agencies, encouraging industry's adoption of these tools can lead to better surveillance and quicker containment of outbreaks. Real-time data sharing with authorities (with appropriate confidentiality safeguards) means that contamination patterns or adulteration incidents can be spotted and acted upon collaboratively. The practical implication is that stakeholders should invest in not just the technologies, but also in the capabilities to use them effectively—this includes training workers in digital skills, upgrading information technology (IT) infrastructure (bandwidth, cloud services, cybersecurity), and developing standard operating procedures that incorporate digital inputs into decision-making. It may also involve new forms of collaboration: companies might need to form data-sharing partnerships or consortia, given that the value of many Industry 4.0 solutions grows with network participation. Importantly, the cost of inaction is rising as more supply chains become real-time and transparent; those that remain opaque or reactive could face greater consumer skepticism and higher risk of disastrous safety failures. In short, industry players are encouraged to pilot these technologies on a small scale, learn from the outcomes, and gradually scale up successful interventions.

5.4 Identifying Research Gaps (RQ4)

Despite advancements in applying Industry 4.0 to agrifood quality and safety, research gaps remain. Studies often focus on individual technologies like AI, IoT, or blockchain instead of integrated multi-technology frameworks. The lack of uniform standards in blockchain and IoT hinders data sharing among stakeholders. Additionally, siloed or non-standardized data limits big data effectiveness, highlighting challenges in merging diverse food safety datasets and the need for common data standards.

A significant gap is the scalability and practical adoption of advanced risk management solutions. While pilot studies show promise, there are few reports on long-term, large-scale industry deployments. Barriers such as cost, infrastructure, and resistance to change hinder adoption, particularly for small and medium-sized enterprises (SMEs), which often require support programs to overcome these challenges.

User training and organizational readiness are also noted challenges: simply installing sensors or a blockchain doesn't automatically improve safety—workers and managers must be trained to interpret data and respond appropriately.

As digital technologies become more integrated into food safety systems, they also face increased security risks, including cyber threats that could compromise sensitive supply chain data. There's also a lack of understanding of the human factor; for instance, while crowdsourcing could help gather food safety intelligence from consumers, challenges like verifying data and motivating participation remain unresolved.

Regulatory adaptation is essential and existing food safety regulations must evolve to accommodate AI-driven risk assessments, blockchain traceability systems, and digital monitoring technologies. Several articles call for stronger governmental frameworks to support digital traceability (e.g., standardized regulations for blockchain records, data privacy laws, and legal acceptance of electronic records in cross-border trade). Without supportive policy, individual firms' efforts may have limited impact.

Moreover, the acquisition of performance measurements and validation through standardized key performance indicators (KPIs) to assess real-world impact remains underdeveloped. Consumer trust in digital food traceability and human–machine collaboration also requires further study to balance automation with human expertise.

Lastly, the environmental sustainability of these technologies is not deeply examined—IoT sensors, data centers for big data, etc., have their own carbon and resource footprint. Only a few papers touch on balancing digital transformation with sustainability goals.

Addressing these gaps will require interdisciplinary collaboration, real-world testing, and coordinated efforts between academia, industry, and policymakers to ensure Industry 4.0 technologies are effective, inclusive, and sustainable in agrifood risk management. These gaps present opportunities for future research and pilot projects to push the field from conceptual promise to widespread practice.

5.5 Addressing Future Trends

Building on the identified gaps, future research should pursue several avenues to fully harness Industry 4.0 for quality and safety risks in the agrifood supply chain. Future research should pursue targeted investigations to advance the practical adoption of Industry 4.0 (I4.0) technologies in agrifood supply chain (AFSC) risk management. While the conceptual value of digitalization is widely acknowledged, more empirical, field-based, and sector-specific studies are needed.

One clear trend is the move toward AI-driven predictive systems. As data accumulates from IoT devices and digital records, more sophisticated machine learning models (e.g., deep learning, ensemble approaches) are expected to play a role in forecasting risks (e.g., predicting contamination outbreaks or equipment failures before they happen). A question to be answered is if predictive analytics (for example, AI, digital twins, or other predictive technologies) can improve shelf-life forecasting in cold chain logistics by combining climate, transport, and microbial data. A predictive model leveraging multi-source data should be developed and validated through longitudinal studies of perishable products. This can help optimize logistics decisions, reduce waste, and better align safety thresholds with dynamic conditions.

Another trend is the expansion of blockchain in agrifood—moving from pilot projects to industry-wide platforms. As interoperability improves, we may see networks of multiple blockchains or blockchain integrated with other systems (for example, linking IoT sensor outputs directly to blockchain records for automated, real-time traceability updates). Precision livestock farming (PLF) tools (like biosensors on animals) currently help on-farm welfare and health monitoring; future systems may feed that farm data forward into the supply chain's blockchain or analytics platforms to provide early warnings of potential safety issues (e.g., if a dairy farm's sensors detect a cow with a disease, milk from that batch can be flagged). Similarly, drone and satellite data in crop farming could integrate with supply chain systems to predict yield and quality, thereby helping downstream processors prepare and control for any issues. But what needs to be studied are the key interoperability and data governance challenges in integrating these systems with attention to cybersecurity and standardization protocols.

Also, a trend focused on sustainability, resilience, and adoption of I4.0 technologies. Future solutions are expected to not only manage day-to-day quality but also help supply chains withstand shocks—whether pandemics, climate-change-driven weather extremes, or other disruptions. For example, the experience of COVID-19 has accelerated interest in digital platforms for supply chain flexibility and risk sharing. There is a push towards building systems that are resilient by design, using digital twins and simulations to test "what-if" scenarios for disruptions. Yet another question that prevails is what factors influence the interpretability and adoption of these food safety prediction systems among industries. Case studies can be conducted alongside interviews with quality assurance managers to evaluate whether AI outputs are actionable and trustworthy, identifying barriers to adoption and training needs.

As automation increases, studies should explore optimal human–machine collaboration in food safety contexts. For example, how can augmented reality training improve a worker's ability to manage a sensor alert, or how can AI decision support be presented so that quality control managers trust and correctly interpret the recommendations?

Finally, an exciting future trend is the involvement of consumers as part of the digital ecosystem. Crowdsourced data and mobile apps could significantly augment official data—e.g., consumers reporting real-time issues to detect outbreaks faster. Integrating consumer-facing transparency tools (like QR codes on packaging that link to blockchain data) can close the loop of information, empowering customers to make safer choices and even incentivize producers to maintain high quality. So, how does consumer-facing digital transparency (e.g., blockchain-backed QR codes) influence trust and food safety behavior? Field experiments in retail settings can measure the impact of traceability tools on consumer purchasing decisions, supported by surveys and behavioral analytics. This can inform both digital labeling strategies and regulatory policy.

6 Conclusions

In the past decade, global agrifood supply chains have started to undergo a major change driven by Industry 4.0 technologies. Effective management of risks in food quality and safety is crucial for safeguarding consumer health, complying with regulations, and maintaining supply chain integrity. As food supply chains become more global, industry encounters increasing challenges such as contamination, fraud, supply disruptions, and environmental hazards. To tackle these risks, modern technologies including blockchain, IoT, artificial intelligence (AI), big data, and predictive analytics are utilized to establish proactive, data-informed risk management systems. These advancements assist in identifying potential threats, reducing contamination risks, and improving the traceability and strength of food production and distribution networks. In summary, as technology progresses, the future of food safety risk management will be characterized by a deeper integration of AI, blockchain, and IoT into predictive, data-informed frameworks. Companies and regulatory bodies need to adopt digital transformation to boost supply chain resilience, enhance quality control, and proactively address emerging risks. Collaborative initiatives among industry leaders, policymakers, and technology developers will be vital in creating a more secure, transparent, and sustainable food system. Ultimately, transitioning towards intelligent, data-driven risk management is not solely about improving food safety; it is also about safeguarding public health, building consumer trust, and promoting long-term sustainability in global food supply chains. The coming decade of research will likely strengthen the integration of digital technologies in food supply chains, making them more intelligent and resilient. The goal is to create a farm-to-fork system where every key variable is monitored, and data flows sustainably. Accomplishing this will necessitate not only technological advancements but also addressing socio-economic and regulatory aspects through careful research and collaboration.

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Declarations

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7. References

1. Donaghy JA, Danyluk MD, Ross T, Krishna B, Farber J (2021) Big data impacting dynamic food safety risk management in the food chain. Front Microbiol 12:668196. https://doi.org/10.3389/fmicb.2021.668196
2. Derakhti A, Santibanez Gonzalez ED, Mardani A (2022) Industry 4.0 and beyond: a review of the literature on the challenges and barriers facing the agri-food supply chain. Sustainability 15(6):5078. https://doi.org/10.3390/su15065078
3. Liu Z, Wang S, Zhang Y, Feng Y, Liu J, Zhu H (2023) Artificial intelligence in food safety: a decade review and bibliometric analysis. Foods 12(6):1242. https://doi.org/10.3390/foods12061242
4. Hassoun A, Aït-Kaddour A, Abu-Mahfouz AM, Rathod NB, Bader F, Barba FJ, Biancolillo A, Cropotova J, Galanakis CM, Režek Jambrak A, Lorenzo JM, Müge I, Ozogul F, Regenstein J (2023a) The fourth industrial revolution in the food industry—Part I: industry 4.0 technologies. Crit Rev Food Sci Nutr 63(23):6547–6563. https://doi.org/10.1080/10408398.2022.2034735
5. Morella P, Lambán MP, Royo J, Sánchez JC (2021) Study and analysis of the implementation of 4.0 technologies in the agri-food supply chain: a state of the art. Agronomy 11(12):2526. https://doi.org/10.3390/agronomy11122526
6. Buyuktepe O, Catal C, Kar G, Bouzembrak Y, Marvin H, Gavai A (2023) Food fraud detection using explainable artificial intelligence. Expert Syst 42(1):e13387. https://doi.org/10.1111/exsy.13387
7. Qian J, Shi C, Wang S, Song Y, Fan B, Wu X (2018) Cloud-based system for rational use of pesticide to guarantee the source safety of traceable vegetables. Food Control 87:192–202. https://doi.org/10.1016/j.foodcont.2017.12.015
8. Yadav VS, Singh AR, Raut RD, Mangla SK, Luthra S, Kumar A (2022) Exploring the application of Industry 4.0 technologies in the agricultural food supply chain: a systematic literature review. Computers and Industrial Engi 169:108304. https://doi.org/10.1016/j.cie.2022.108304
9. Ehuwa O, Jaiswal AK, Jaiswal S (2021) Salmonella, food safety, and food handling practices. Foods 10(5):1–16. https://doi.org/10.3390/foods10050907
10. Jagtap S, Rahimifard S (2019) The digitization of food manufacturing to reduce waste: case paper of a ready meal factory. Waste Manag 87:387–397. https://doi.org/10.1016/j.wasman.2019.02.017
11. Prause L, Hackfort S, Lindgren M (2020) Digitalization and the third food regime. Agric Hum Values 38:641–655. https://doi.org/10.1007/s10460-020-10161-2
12. Barbosa MW (2021) Uncovering research streams on agri-food supply chain management: a bibliometric paper. Glob Food Sec 28:100517. https://doi.org/10.1016/j.gfs.2021.100517
13. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD et al (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372:n71. https://doi.org/10.1136/bmj.n71For more information, visit: (http://www.prisma-statement.org/)
14. Xin H, Fang X, Wang Y, Hong S, Wang T (2015) Study on risk assessment of meat and meat products quality safety based on risk matrix. In Proceedings of the 2015 International Conference on Mechatronics, Electronic, Industrial and Control Engineering (pp. 423–426). Atlantis Press. https://doi.org/10.2991/meic-15.2015.98
15. Rosales FP, Oprime PC, Royer A, Batalha MO (2020) Supply chain risks: findings from Brazilian slaughterhouses. Supply Chain Manag Int J 25(3):342–357. https://doi.org/10.1108/SCM-03-2019-0130

16. Moazzam M, Akhtar P, Garnevska E, Marr NE (2018) Measuring agri-food supply chain performance and risk through a new analytical framework: a case study of New Zealand dairy. Prod Plan Control 29(15):1258–1274. https://doi.org/10.1080/09537287.2018.1522847
17. Heinzova R, Vichova K, Peterek K, Strohmandl J (2022) Supply chain risk management in dairy industry of the Czech Republic. Acta Logist 9(4):441–448. https://doi.org/10.22306/al.v9i4.343
18. Wahyuni HC, Sumarmi W, Saidi IA (2018) Food safety risk analysis of food supply chain in small and medium enterprises (case study: supply chain of fish). Int J Eng Technol 7(2.14):229–233. https://doi.org/10.14419/ijet.v7i2.14.11605
19. Tang T, Wang M, Zhang Y, Yang Y, Li J, Sun J (2017) Agricultural products quality and safety monitoring system research based on supply chain. In *Proceedings of the 2017 7th International Conference on Social Network, Communication and Education (SNCE 2017)* (pp. 351–360). Atlantis Press. https://doi.org/10.2991/snce-17.2017.72
20. Imbiri S, Rameezdeen R, Chileshe N, Statsenko L (2021) A novel taxonomy for risks in agribusiness supply chains: a systematic literature review. Sustainability 13(16):9217. https://doi.org/10.3390/su13169217
21. Ali SM, Moktadir MA, Kabir G, Chakma J, Rumi MJU, Islam MT (2019) Framework for evaluating risks in food supply chain: implications in food wastage reduction. J Clean Prod 228:786–800. https://doi.org/10.1016/j.jclepro.2019.04.322
22. Ummi N, Marimin Noor E, and Romli M (2023) Risk management in reverse supply chain for sustainable agri-food industry: a systematic literature review and future research agenda. Oper Supply Chain Manag 16(3):323–339. https://doi.org/10.31387/oscm12345
23. Nyamah EY, Jiang Y, Feng Y, Nyamah EY (2017) Agri-food supply chain performance: an empirical impact of risk. Manag Decis 55(5):872–891. https://doi.org/10.1108/MD-01-2016-0049
24. Chan HK, Griffin J, Lim JJ, Zeng F, Chiu ASF (2018) The impact of 3D printing technology on the supply chain: manufacturing and legal perspectives. Int J Prod Econ 205:156–162. https://doi.org/10.1016/j.ijpe.2018.09.009
25. Longhitano GA, Nunes GB, Candido G, da Silva JVL (2021) The role of 3D printing during the COVID-19 pandemic: a review. Progress in Additive Manufacturing 6(1):19–37. Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s40964-020-00159-x
26. Cyplik P, Zwolak M (2022) Industry 4.0 and 3D print: a new heuristic approach for decoupling point in future supply chain management. LogForum 18(2):161–171. https://doi.org/10.17270/J.LOG.2021.733
27. Derossi A, Bhandari B, van Bommel K, Noort M, Severini C (2021) Could 3D food printing help to improve the food supply chain resilience against disruptions such as caused by pandemic crises? Int J Food Sci Technol 56:4338–4355. https://doi.org/10.1111/ijfs.15224
28. Zhang Q, Wang W, Yang Z, Wang X, Xu W, Huang K, Luo Y, He X, Cheng N (2021) A portable 3D-printed biosensing device for rapid detection of genetically modified maize MON810. Sens Actuators B Chem 349:130748. https://doi.org/10.1016/j.snb.2021.130748
29. Malhotra S, Pham DS, Lau MPH, Nguyen AH, Cao H (2022) A low-cost, 3D-printed biosensor for rapid detection of *Escherichia coli*. Sensors 22(6):2382. https://doi.org/10.3390/s22062382
30. Rogers H, Srivastava M (2021) Emerging sustainable supply chain models for 3D food printing. Sustainability 13(21):12085. https://doi.org/10.3390/su132112085
31. Benefo EO, Karanth S, Pradhan AK (2022) Applications of advanced data analytic techniques in food safety and risk assessment. Curr Opin Food Sci 48:100937. https://doi.org/10.1016/j.cofs.2022.100937
32. Benefo EO, Tingler A, White M, Cover J, Torres L, Broussard C, Shirmohammadi A, Pradhan AK, Patra D (2022) Ethical, legal, social, and economic (ELSE) implications of artificial intelligence at a global level: a scientometrics approach. AI Ethics. https://doi.org/10.1007/s43681-021-00124-6
33. Kudashkina K, Corradini MG, Thirunathan P, Yada RY, Fraser EDG (2022) Artificial intelligence technology in food safety: a behavioral approach. Trends Food Sci Technol 123:376–381. https://doi.org/10.1016/j.tifs.2022.03.021
34. Zuo M, Cao C, Zhang Q, Wang C, Wang H (2017) Study on quality and safety prediction of meat products based on CNN. *DEStech Transactions on Computer Science and Engineering*, (iceiti). https://doi.org/10.12783/dtcse/iceiti2017/18874
35. Ashqar BA, Abu-Naser SS (2018) Image-based tomato leaves diseases detection using deep learning. International Journal of Academic Engineering Research 2(12):10–16
36. Zhou L, Zhang C, Liu F, Qiu Z, He Y (2019) Application of deep learning in food: a review. Compr Rev Food Sci Food Saf 18(6):1793–1811. https://doi.org/10.1111/1541-4337.12492

37. Nogales A, Díaz-Morón R, García-Tejedor ÁJ (2022) A comparison of neural and non-neural machine learning models for food safety risk prediction with European Union RASFF data. Food Control 134:108697. https://doi.org/10.1016/j.foodcont.2021.108697
38. Bouzembrak Y, Marvin HJP (2016) Prediction of food fraud type using data from rapid alert system for food and feed (RASFF) and Bayesian network modelling. Food Control 61:180–187. https://doi.org/10.1016/j.foodcont.2015.09.026
39. Heydarbakian S, Spehri M (2022) Interpretable machine learning to improve supply chain resilience: an Industry 4.0 recipe. IFAC-Papers OnLine 55(10):2834–2839. https://doi.org/10.1016/j.ifacol.2022.10.202
40. Xu J, Wang Z, Zhang X, Yu J, Cui X, Zhou Y, Zhao Z (2022) A rice security risk assessment method based on the fusion of multiple machine learning models. Agriculture (Basel) 12(6):815. https://doi.org/10.3390/agriculture12060815
41. Wang X, Liu C, van der Fels-Klerx HJ (2022) Regional prediction of multi-mycotoxin contamination of wheat in Europe using machine learning. Food Res Int 159:111588. https://doi.org/10.1016/j.foodres.2022.111588
42. Branstad-Spates EH, Castano-Duque L, Mosher GA, Hurburgh CR Jr, Owens P, Winzeler E, Rajasekaran K, Bowers EL (2023) Gradient boosting machine learning model to predict aflatoxins in Iowa corn. Front Microbiol 14:1248772. https://doi.org/10.3389/fmicb.2023.1248772
43. Friedlander A, Zoellner C (2020) Artificial intelligence opportunities to improve food safety at retail. Food Prot Trends 40(4):272–278. Retrieved May 19, 2023, from https://www.foodprotection.org/publications/food-protection-trends/archive/2020-07-artificialintelligence-opportunities-to-improve-food-safety-at-retail/
44. Tao D, Zhang D, Hu R, Rundensteiner E, Feng H (2021) Crowdsourcing and machine learning approaches for extracting entities indicating potential foodborne outbreaks from social media. Sci Rep 11:21678. https://doi.org/10.1038/s41598-021-00766-w
45. Wu L-Y, Weng S-S (2021) Ensemble learning models for food safety risk prediction. Sustainability 13(21):12291. https://doi.org/10.3390/su132112291
46. Wang X, Bouzembrak Y, Oude Lansink AGJM, van der Fels-Klerx HJ (2022) Designing a monitoring program for aflatoxin B1 in feed products using machine learning. NPJ Sci Food 6:40. https://doi.org/10.1038/s41538-022-00154-2
47. Lim MK, Li Y, Wang C, Tseng M-L (2022) Prediction of cold chain logistics temperature using a novel hybrid model based on the mayfly algorithm and extreme learning machine. Ind Manag Data Syst 122(3):819–840. https://doi.org/10.1108/IMDS-10-2021-0607
48. Kasza G, Csenki E, Szakos D, Izsó T (2022) The evolution of food safety risk communication: models and trends in the past and the future. Food Control 138:109025. https://doi.org/10.1016/j.foodcont.2022.109025
49. Makridis G, Mavrepis P, Kyriazis D (2023) A deep learning approach using natural language processing and time-series forecasting towards enhanced food safety. Mach Learn 112:1287–1313. https://doi.org/10.1007/s10994-022-06151-6
50. Chen Y, Wu C, Zhang Q, Wu D (2023) Review of visual analytics methods for food safety risks. NPJ Sci Food 7:49. https://doi.org/10.1038/s41538-023-00226-x
51. Karanth S, Benefo EO, Patra D, Pradhan AK (2023) Importance of artificial intelligence in evaluating climate change and food safety risk. J Agric Food Res 11:100485. https://doi.org/10.1016/j.jafr.2023.100485
52. Karanth S, Patel J, Shirmohammadi A, Pradhan AK (2023) Machine learning to predict foodborne salmonellosis outbreaks based on genome characteristics and meteorological trends. Curr Res Food Sci 6:100525. https://doi.org/10.1016/j.crfs.2023.100525
53. Trabelsi M, Casprini E, Fiorini N, Zanni L (2023) Unleashing the value of artificial intelligence in the agri-food sector: where are we? Br Food J 125(13):482–515. https://doi.org/10.1108/bfj-11-2022-1014
54. Qian C, Murphy SI, Orsi RH, Wiedmann M (2023) How can AI help improve food safety? Annu Rev Food Sci Technol 14:517–538. https://doi.org/10.1146/annurev-food-060721-013815
55. Ding L, Zhou J-J (2021) Research on risk evaluation of intelligent supply chain under food safety mode. In Y. Xing (Ed.), Fifth International Conference on Traffic Engineering and Transportation System (ICTETS 2021) (Proc. SPIE Vol. 12058, 120586B). SPIE. https://doi.org/10.1117/12.2613655
56. Sapienza S, Vedder A (2023) Principle-based recommendations for big data and machine learning in food safety: the P-SAFETY model. AI Soc 38:5–20. https://doi.org/10.1007/s00146-021-01282-1

57. Deng X, Cao S, Horn AL (2021) Emerging applications of machine learning in food safety. Annu Rev Food Sci Technol 12:513–538. https://doi.org/10.1146/annurev-food-071720-024112
58. Mourtzis D, Vlachou E, Giannoulis C, Siganakis E, Zogopoulos V (2016) Applications for frugal product customization and design of manufacturing networks. Procedia CIRP 52:228–233. https://doi.org/10.1016/j.procir.2016.07.055
59. Nee AYC, Ong SK (2013) Virtual and augmented reality applications in manufacturing. IFAC Proceedings Volumes 46(9):15–26. https://doi.org/10.3182/20130619-3-RU-3018.00637
60. Marvin HJP, Janssen EM, Bouzembrak Y, Hendriksen PJM, Staats M (2017) Big data in food safety: an overview. Crit Rev Food Sci Nutr 57(11):2286–2295. https://doi.org/10.1080/10408398.2016.1257481
61. Møller FT, Mølbak K, Ethelberg S (2018) Analysis of consumer food purchase data used for outbreak investigations: a review. Euro Surveill 23(24):1700503. https://doi.org/10.2807/1560-7917.ES.2018.23.24.1700503
62. Kovac J (2019) Precision food safety: a paradigm shift in detection and control of foodborne pathogens. mSystems 4:e00164–19. https://doi.org/10.1128/mSystems.00164-19
63. Kovac J, den Bakker H, Carroll LM, Wiedmann M (2017) Precision food safety: a systems approach to food safety facilitated by genomics tools. Trends Anal Chem 96:52–61. https://doi.org/10.1016/j.trac.2017.06.001
64. Ronholm J, Nasheri N, Petronella N, Pagotto F (2016) Navigating microbiological food safety in the era of whole-genome sequencing. Clin Microbiol Rev 29(4):837–857. https://doi.org/10.1128/CMR.00056-16
65. Brown E, Dessai U, McGarry S, Gerner-Smidt P (2019) The use of whole-genome sequencing for food safety and public health in the United States. Foodborne Pathog Dis 16(7):441–450. https://doi.org/10.1089/fpd.2019.2662
66. Kuang XH, Tang D, Zhou ZX (2016) Applying big data to food safety risk monitoring. In *Proceedings of the 2015 International Conference on Software Engineering and Information Technology (SEIT2015)* (pp. 81–84). https://doi.org/10.1142/9789814740104_0036
67. Soon JM, Saguy I (2017) Crowdsourcing: a new conceptual view for food safety and quality. Trends Food Sci Technol 66:63–72. https://doi.org/10.1016/j.tifs.2017.05.008
68. Liu G, Li G, Yang R, Guo L (2018) Improving food safety in the supply chain based on big data. E3S Web Conf 53:03084. https://doi.org/10.1051/e3sconf/20185303084
69. Tiozzo B, Ruzza M, Rizzoli V, D'Este L, Giaretta M, Ravarotto L (2020) Biological, chemical, and nutritional food risks and food safety issues from Italian online information sources: web monitoring, content analysis, and data visualization. J Med Internet Res 22(12):e23438. https://doi.org/10.2196/23438
70. Katikou P (2021) Digital technologies and open data sources in marine biotoxins' risk analysis: the case of ciguatera fish poisoning. Toxins 13(10):692. https://doi.org/10.3390/toxins13100692
71. Talari G, Cummins E, McNamara C, O'Brien J (2022) State of the art review of big data and web-based decision support systems (DSS) for food safety risk assessment with respect to climate change. Trends Food Sci Technol 126:192–204. https://doi.org/10.1016/j.tifs.2022.06.002
72. Vieira AAC, Dias L, Santos MY, Pereira GAB, Oliveira J (2020) Supply chain risk management: an interactive simulation model in a big data context. Procedia Manuf 42:140–145. https://doi.org/10.1016/j.promfg.2020.02.062
73. Salah K, Nizamuddin N, Jayaraman R, Omar M (2019) Blockchain-based soybean traceability in agricultural supply chain. IEEE Access 7:73295–73305. https://doi.org/10.1109/ACCESS.2019.2918000
74. Hao Z, Mao D, Zhang B, Zuo M, Zhao Z (2020) A novel visual analysis method of food safety risk traceability based on blockchain. Int J Environ Res Public Health 17(7):2300. https://doi.org/10.3390/ijerph17072300
75. Tian F (2016) An agri-food supply chain traceability system for China based on RFID & blockchain technology. In Proceedings of the 2016 13th International Conference on Service Systems and Service Management (ICSSSM) (pp. 1–6). IEEE. https://doi.org/10.1109/ICSSSM.2016.7538424
76. Dayana DS, Kalpana G (2023) A secured blockchain-based approach for decentralized agri-insurance for food crops supply chain. Journal of Theoretical and Applied Information Technology 101(9):3547–3556. https://www.jatit.org/volumes/Vol101No9/28Vol101No9.pdf
77. Tao Q, Cai Z, Cui X (2022) A technological quality control system for rice supply chain. Food Energy Secur 12:e382. https://doi.org/10.1002/fes3.382

78. Wang J, Zhang X, Xu J, Wang X, Li H, Zhao Z, Kong J (2022) Blockchain-based information supervision model for rice supply chains. Computational Intelligence and Neuroscience 2022:2914571. https://doi.org/10.1155/2022/2914571
79. Sugandh U, Nigam S, Khari M, Misra S (2023) An approach for risk traceability using blockchain technology for tracking, tracing, and authenticating food products. Information 14(11):613. https://doi.org/10.3390/info14110613
80. Bosona T, Gebresenbet G (2023) The role of blockchain technology in promoting traceability systems in agri-food production and supply chains. Sensors (Basel) 23(11):5342. https://doi.org/10.3390/s23115342
81. Sugandh U, Nigam S, Khari M (2022) Blockchain technology in agriculture for Indian farmers: a systematic literature review, challenges, and solutions. IEEE Syst Man Cybern Mag 8:36–43. https://doi.org/10.1109/MSMC.2022.3149671
82. Xu Y, Li X, Zeng X, Cao J, Jiang W (2022) Application of blockchain technology in food safety control: current trends and future prospects. Crit Rev Food Sci Nutr 62(10):2800–2819. https://doi.org/10.1080/10408398.2020.1858752
83. İndap Ş, Tanyaş M (2023) Blockchain applications for traceability and food safety in agri-food supply chain: cherry product application. Journal of Enterprise Information Management. Advance online publication. https://doi.org/10.1108/JEIM-03-2023-0165
84. Pakseresht A, Yavari A, Kaliji SA, Hakelius K (2023) The intersection of blockchain technology and circular economy in the agri-food sector. Sustain Prod Consum 35:260–274. https://doi.org/10.1016/j.spc.2022.11.002
85. Longo F, Nicoletti L, Padovano A (2019) Estimating the impact of blockchain adoption in the food processing industry and supply chain. Int J Food Eng 16(5–6):20190109. https://doi.org/10.1515/ijfe-2019-0109
86. Gopi K, Mazumder D, Sammut J, Saintilan N (2019) Determining the provenance and authenticity of seafood: a review of current methodologies. Trends Food Sci Technol 91:294–304. https://doi.org/10.1016/j.tifs.2019.07.010
87. Cuel R, Cangelosi GM (2020) In vino veritas? Blockchain preliminary effects on Italian wine SMEs. In: Agrifoglio R et al (eds) Digital business transformation (Lecture Notes in Information Systems and Organisation, Vol. 38). Springer. https://doi.org/10.1007/978-3-030-47355-6_20
88. Pradana GMT, Djatna T, Hermadi I (2020) Blockchain modeling for traceability information system in supply chain of coffee agroindustry. Proceedings of the 2020 3rd International Conference on Computer and Informatics Engineering (IC2IE) 1–6. https://doi.org/10.1109/IC2IE50715.2020.9274571
89. Cocco L, Mannaro K, Tonelli R, Mariani L, Lodi MB, Melis A, Simone M, Fanti A (2021) A blockchain-based traceability system in agri-food SME: case study of a traditional bakery. IEEE Access 9:61032–61044. https://doi.org/10.1109/ACCESS.2021.3074874
90. Zhang B, Xu J, Wang X, Zhao Z, Chen S, Zhang X (2023) Research on the construction of grain food multi-chain blockchain based on zero-knowledge proof. Foods 12(8):1600. https://doi.org/10.3390/foods12081600
91. Patel D, Sinha A, Bhansali T, Usha G, Velliangiri S (2022) Blockchain in food supply chain. Procedia Comput Sci 215:321–330. https://doi.org/10.1016/j.procs.2022.12.034
92. Ahmad A, Bailey K (2021) Blockchain in food traceability: a systematic literature review. In 2021 32nd Irish Signals and Systems Conference (ISSC) (pp 1–6) IEEE. https://doi.org/10.1109/ISSC52156.2021.9467848
93. Dumitrache I, Caramihai SI, Sacala IS, Moisescu MA (2017) A cyber physical systems approach for agricultural enterprise and sustainable agriculture. In 2017 21st International Conference on Control Systems and Computer Science (CSCS) (pp. 477–482). IEEE. https://doi.org/10.1109/CSCS.2017.102
94. Miskinis C (2019) *The history and creation of the digital twin concept*. Challenge Advisory. Retrieved May 22, 2023 from https://www.challenge.org/insights/digital-twin-history/
95. Bhandal R, Meriton R, Kavanagh RE, Brown A (2022) The application of digital twin technology in operations and supply chain management: a bibliometric review. Supply Chain Manag Int J 27(2):182–206. https://doi.org/10.1108/SCM-01-2021-0053
96. Ivanov D, Dolgui A (2020a) A digital supply chain twin for managing the disruption risks and resilience in the era of industry 4.0. Prod Plan Control 32(9):775–788. https://doi.org/10.1080/09537287.2020.1768450

97. Ivanov D, Dolgui A (2020b) Researchers' perspectives on Industry 4.0: multi-disciplinary analysis and opportunities for operations management. Int J Prod Res 59(7):1924–1940. https://doi.org/10.1080/00207543.2020.1798035
98. Cavalcante IM, Frazzon EM, Forcellini FA, Ivanov D (2019) A supervised machine learning approach to data-driven simulation of resilient supplier selection in digital manufacturing. Int J Inf Manage 49:86–97. https://doi.org/10.1016/j.ijinfomgt.2019.03.004
99. Shrivastava C, Schudel S, Shoji K, Onwude D, Pereira da Silva F, Turan D, Paillart M, Defraeye T (2023) Digital twins for selecting the optimal ventilated strawberry packaging based on the unique hygrothermal conditions of a shipment from farm to retailer. Postharvest Biol Technol 199:112283. https://doi.org/10.1016/j.postharvbio.2023.112283
100. Thibaud M, Chi H, Zhou W, Piramuthu S (2018) Internet of Things (IoT) in high-risk environment, health and safety (EHS) industries: a comprehensive review. Decis Support Syst 108:79–95. https://doi.org/10.1016/j.dss.2018.02.005
101. Kumar D, Dwivedi RK (2023) Blockchain and IoT based smart agriculture and food supply chain system. 2023 IEEE 8th International Conference for Convergence in Technology (I2CT), 1–5. https://doi.org/10.1109/I2CT51068.2023.10090897
102. Balasundram SK, Shamshiri RR, Sridhara S, Rizan N (2023) The role of digital agriculture in mitigating climate change and ensuring food security: an overview. Sustainability 15(6):5325. https://doi.org/10.3390/su15065325
103. Capello F, Toja M, Trapani N (2016) A real-time monitoring service based on industrial internet of things to manage agrifood logistics. In *6th International Conference on Information Systems, Logistics and Supply Chain (ILS Conference 2016)*, Bordeaux, France. Retrieved February 2, 2023, from https://www.researchgate.net/publication/313770425_A_Real-Time_Monitoring_Service_based_on_Industrial_Internet_of_Things_to_manage_agrifood_logistics
104. Ting SL, Tse YK, Ho GTS, Chung SH, Pang G (2014) Mining logistics data to assure the quality in a sustainable food supply chain: a case in the red wine industry. Int J Prod Econ 152:200–209. https://doi.org/10.1016/j.ijpe.2013.12.010
105. Aung MM, Chang YS (2014) Temperature management for the quality assurance of a perishable food supply chain. Food Control 40:198–207. https://doi.org/10.1016/j.foodcont.2013.11.016
106. Beker I, Delić M, Milisavljević S, Gošnik D, Ostojić G, Stankovski S (2016) Can IoT be used to mitigate food supply chain risk? Int J Ind Eng Manag 7(1):43–48
107. Ben-Tzur I, Sharshevsky H, Mangut-Leiba S, Dagar A (2015) The power of an integrated monitoring technology system for minimizing quality and food safety risks in fresh produce supply chain. Acta Horticulturae, 1079, 351–357. https://doi.org/10.17660/ActaHortic.2015.1079.44
108. Nastasijević I, Branković Lazić I, Petrović Z (2019) Precision livestock farming in the context of meat safety assurance system. IOP Conference Series: Earth and Environmental Science 333:012014. https://doi.org/10.1088/1755-1315/333/1/012014
109. Tsang YP, Choy KL, Wu CH, Ho GTS, Lam CHY, Koo PS (2018) An internet of things (IoT)-based risk monitoring system for managing cold supply chain risks. Ind Manag Data Syst 118(7):1432–1462. https://doi.org/10.1108/IMDS-09-2017-0384
110. Zhang S, Liao J, Wu S, Zhong J, Xue X (2021b) A traceability public service cloud platform incorporating IDcode system and colorful QR code technology for important products. Math Probl Eng 2021:5535535. https://doi.org/10.1155/2021/5535535
111. Kong J, Yang C, Wang J, Wang X, Zuo M, Jin X, Lin S (2021) Deep-stacking network approach by multisource data mining for hazardous risk identification in IoT-based intelligent food management systems. Computational Intelligence and Neuroscience 2021:1194565. https://doi.org/10.1155/2021/1194565
112. Chen T, Ding K, Yu Z, Li G, Dong Y (2021) Smart supervision for food safety in food service establishments in China: challenges and solutions. J Food Prot 84(6):938–945. https://doi.org/10.4315/JFP-20-370
113. Ruamsuke T, Ongkunaruk P (2021) Supply chain analysis of import fresh fruit business in Thailand using the supply chain operations reference (SCOR) model. E3S Web Conf 316:02014. https://doi.org/10.1051/e3sconf/202131602014
114. Mohammed M, Riad K, Alqahtani N (2022) Design of a smart IoT-based control system for remotely managing cold storage facilities. Sensors 22(13):4680. https://doi.org/10.3390/s22134680

115. Khan AU, Ali Y, Pamucar D, Vasa L (2022) Risk management for cold supply chain: case of a developing country. Acta Polytech Hung 19(8):161–185. https://doi.org/10.12700/APH.19.8.2022.8.9
116. Kuizinaitė J, Morkūnas M, Volkov A (2023) Assessment of the most appropriate measures for mitigation of risks in the agri-food supply chain. Sustainability 15(12):9378. https://doi.org/10.3390/su15129378
117. Mishra N, Jain SK, Agrawal N, Jain NK, Wadhawan N, Panwar NL (2023) Development of drying system by using internet of things for food quality monitoring and controlling. Energy Nexus 11:100219. https://doi.org/10.1016/j.nexus.2023.100219
118. Ataei Kachouei M, Kaushik A, Ali MA (2023) Internet of things-enabled food and plant sensors to empower sustainability. Adv Intell Syst 5(12):2300321. https://doi.org/10.1002/aisy.202300321
119. Purwandoko PB, Seminar KB, Sutrisno, Sugiyanta (2019) Development of a smart traceability system for the rice agroindustry supply chain in Indonesia. Information 10(10):288. https://doi.org/10.3390/info10100288
120. Zhang G, Li G, Peng J (2020) Risk assessment and monitoring of green logistics for fresh produce based on a support vector machine. Sustainability 12(18):7569. https://doi.org/10.3390/su12187569
121. Hui D (2021) Study on risk control of fresh supply chain demand interruption under computer e-commerce environment. J Phys Conf Ser 1992(3):032053. https://doi.org/10.1088/1742-6596/1992/3/032053
122. Zheng M, Zhang S, Zhang Y, Hu B (2021) Construct food safety traceability system for people's health under the internet of things and big data. IEEE Access 9:70571–70583. https://doi.org/10.1109/ACCESS.2021.3078330
123. Alam W, Mehmood A, Ali K, Javaid U, Alharbi S, Iqbal J (2018) Nonlinear control of a flexible joint robotic manipulator with experimental validation. Strojniški vestnik – Journal of Mechanical Engineering 64:47–55. https://doi.org/10.5545/sv-jme.2017.4786
124. Khan ZH, Khalid A, Iqbal J (2018) Towards realizing robotic potential in future intelligent food manufacturing systems. Innov Food Sci Emerg Technol 48:11–24. https://doi.org/10.1016/j.ifset.2018.05.011
125. Gray JO, Davis ST, Caldwell DG (2013) Robotics in the food industry: An introduction. In D. G. Caldwell (Ed.) Robotics and automation in the food industry: Current and future technologies (pp. 21–35). Woodhead Publishing. https://doi.org/10.1533/9780857095763.1.21
126. Grenzdörffer GJ, Engel A, Teichert B (2008) The photogrammetric potential of low-cost UAVs in forestry and agriculture. Int Arch Photogramm Remote Sens Spat Inf Sci 37:1207–1213. Retrieved February 2, 2023, from https://www.isprs.org/proceedings/xxxvii/congress/1_pdf/206.pdf
127. Saari H, Pellikka I, Pesonen L, Tuominen S, Heikkilä J, Holmlund C, Mäkynen J, Ojala K, Antila T (2011) Unmanned aerial vehicle (UAV) operated spectral camera system for forest and agriculture applications. In Proceedings of SPIE Remote Sensing for Agriculture, Ecosystems, and Hydrology XIII (Vol 8174, pp 170–184). SPIE. https://doi.org/10.1117/12.897585
128. Trienekens J, Zuurbier P (2008) Quality and safety standards in the food industry: developments and challenges. Int J Prod Econ 113(1):107–122. https://doi.org/10.1016/j.ijpe.2007.02.050
129. Erzincanli F, Sharp J (1997) A classification system for robotic food handling. Food Control 8(4):191–197. https://doi.org/10.1016/S0956-7135(97)00048-0
130. LeBlanc DI, Villeneuve S, Hashemi Beni L, Otten A, Fazil A, McKellar R, Delaquis P (2015) A national produce supply chain database for food safety risk analysis. J Food Eng 147:24–38. https://doi.org/10.1016/j.jfoodeng.2014.09.026
131. Zhang Y, Krogmeier JV, Ault A, and Buckmaster D (2020). APT3: automated product traceability trees generated from GPS tracks. Trans ASABE 63(3):571–582. https://doi.org/10.13031/trans.13604
132. Aung MM, Chang YS (2014) Traceability in a food supply chain: safety and quality perspectives. Food Control 39:172–184. https://doi.org/10.1016/j.foodcont.2013.11.007
133. Moriarity RJ, Liberda EN, Tsuji LJS (2020) Using a geographic information system to assess local scale methylmercury exposure from fish in nine communities of the Eeyou Istchee territory (James Bay, Quebec, Canada). Environ Res 191:110147. https://doi.org/10.1016/j.envres.2020.110147
134. Bogataj D, Bogataj M, Hudoklin D (2017) Reprint of "Mitigating risks of perishable products in the cyber-physical systems based on the extended MRP model." Int J Prod Econ 194:113–125. https://doi.org/10.1016/j.ijpe.2017.11.004

135. Demartini M, Pinna C, Tonelli F, Terzi S, Sansone C, Testa C (2018) Food industry digitalization: from challenges and trends to opportunities and solutions. IFAC-PapersOnLine 51(11):1371–1378. https://doi.org/10.1016/j.ifacol.2018.08.337
136. Massaro A, Galiano A (2020) Re-engineering process in a food factory: an overview of technologies and approaches for the design of pasta production processes. Prod Manuf Res 8(1):80–100. https://doi.org/10.1080/21693277.2020.1749180
137. Ivanov D, Dolgui A, Sokolov B (2019) The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. Int J Prod Res 57(3):829–846. https://doi.org/10.1080/00207543.2018.1488086
138. Ahmed SF, Alam MSB, Hoque M, Lameesa A, Afrin S, Farah T, Kabir M, Shafiullah GM, Muyeen S (2023) Industrial internet of things enabled technologies, challenges, and future directions. Comput Electr Eng 110:108847. https://doi.org/10.1016/j.compeleceng.2023.108847
139. Emmanouilidis C, Bakalis S (2020) Digital technology enablers for resilient and customer-driven food value chains. In Advances in Production Management Systems. The Path to Digital Transformation and Innovation of Production Management Systems: IFIP WG 5.7 International Conference, APMS 2020, Novi Sad, Serbia, August 30–September 3, 2020, Proceedings, Part II (pp. 649–657). Springer. https://doi.org/10.1007/978-3-030-57997-5_75
140. Krstić M, Agnusdei GP, Tadić S, Miglietta PP (2023) Prioritization of e-traceability drivers in the agri-food supply chains. Agric Food Econ 11:42. https://doi.org/10.1186/s40100-023-00284-5
141. Tripoli M, Schmidhuber J (2020) Optimising traceability in trade for live animals and animal products with digital technologies. Rev Sci Tech Off Int Epiz 39(1):235–244. https://doi.org/10.20506/rst.39.1.3076
142. Dai Q, Liu X, Zhang M, Mu T, and Ren Y (2022) Blockchain-based risk tracing of animal-derived food supply chain. In Proceedings of the 2022 2nd International Conference on Algorithms, High Performance Computing and Artificial Intelligence, vol 3331. CEUR Workshop Proceedings, pp 6–11. https://ceur-ws.org/Vol-3331/
143. Yadav S, Luthra S, Garg D (2021) Modelling internet of things (IoT)-driven global sustainability in multi-tier agri-food supply chain under natural epidemic outbreaks. Environ Sci Pollut Res 28:16633–16654. https://doi.org/10.1007/s11356-020-11676-1
144. Schmidt D, Butturi MA, Sellitto MA (2023) Opportunities of digital transformation in post-harvest activities: a single case study of an engineering solutions provider. AgriEngineering 5(3):1226–1242. https://doi.org/10.3390/agriengineering5030078
145. Ren Q-S, Fang K, Yang X-T, Han J-W (2022) Ensuring the quality of meat in cold chain logistics: a comprehensive review. Trends Food Sci Technol 119:133–151. https://doi.org/10.1016/j.tifs.2021.12.006
146. Mu W, Kleter GA, Bouzembrak Y, Dupouy E, Frewer LJ, Al Natour FNR, Marvin HJP (2023) Making food systems more resilient to food safety risks by including artificial intelligence, big data, and internet of things into food safety early warning and emerging risk identification tools. Compr Rev Food Sci Food Saf 23(1):e13296. https://doi.org/10.1111/1541-4337.13296
147. Dadi V, Nikhil SR, Mor RS, Agarwal T, Arora S (2021) Agri-food 4.0 and innovations: revamping the supply chain operations. Prod Eng Arch 27(2):75–89. https://doi.org/10.30657/pea.2021.27.10
148. Al-Banna A, Yaqot M, Menezes B (2023) Roadmap to digital supply chain resilience under investment constraints. Prod Manuf Res 11(1):2194943. https://doi.org/10.1080/21693277.2023.2194943
149. Kim S-S, Kim S (2022) Impact and prospect of the fourth industrial revolution in food safety: mini-review. Food Sci Biotechnol 31(4):399–406. https://doi.org/10.1007/s10068-022-01047-6
150. Galanakis CM, Rizou M, Aldawoud TMS, Ucak I, Rowan NJ (2021) Innovations and technology disruptions in the food sector within the COVID-19 pandemic and post-lockdown era. Trends Food Sci Technol 110:193–200. https://doi.org/10.1016/j.tifs.2021.02.002
151. Krupitzer C, Noack T, Borsum C (2022) Digital food twins combining data science and food science: system model, applications, and challenges. Processes 10(9):1781. https://doi.org/10.3390/pr10091781
152. Gillespie J, Da Costa TP, Cadden T, Condell J, Cowderoy T, Ramsey E, Murphy F, Kull M, Gallagher R, Ramanathan R (2022) Real-time anomaly detection in cold chain transportation using IoT technology. Sustainability 15(3):2255. https://doi.org/10.3390/su15032255
153. Patel AS, Brahmbhatt MN, Bariya AR, Nayak JB, Singh VK (2023) Blockchain technology in food safety and traceability concern to livestock products. Heliyon 9(5):e16526. https://doi.org/10.1016/j.heliyon.2023.e16526

154. Hassoun A, Garcia-Garcia G, Trollman H, Jagtap S, Parra-López C, Cropotova J, Bhat Z, Centobelli P, Aït-Kaddour A (2023b) Birth of dairy 4.0: opportunities and challenges in adoption of fourth industrial revolution technologies in the production of milk and its derivatives. Curr Res Food Sci 7:100535. https://doi.org/10.1016/j.crfs.2023.100535
155. Sinha A, Priyadarshi P, Bhushan M, Debbarma D (2021) Worldwide trends in the scientific production of literature on traceability in food safety: a bibliometric analysis. Artificial Intelligence in Agriculture 5:252–261. https://doi.org/10.1016/j.aiia.2021.11.002
156. Rainero C, Modarelli G (2021) Food tracking and blockchain-induced knowledge: a corporate social responsibility tool for sustainable decision-making. Br Food J 123(12):4284–4308. https://doi.org/10.1108/BFJ-10-2020-0921
157. Hassoun A, Boukid F, Pasqualone A, Bryant CJ, García García G, Parra-López C, Jagtap S, Trollman H, Cropotova J, Barba FJ (2022) Emerging trends in the agri-food sector: digitalisation and shift to plant-based diets. Curr Res Food Sci 5:2261–2269. https://doi.org/10.1016/j.crfs.2022.11.010
158. Iftekhar A, Cui X, Hassan M, Afzal W (2020) Application of blockchain and Internet of Things to ensure tamper-proof data availability for food safety. Journal of Food Quality 2020:5385207. https://doi.org/10.1155/2020/5385207
159. Spieske A, Birkel H (2021) Improving supply chain resilience through industry 4.0: a systematic literature review under the impressions of the COVID-19 pandemic. Comput Ind Eng 158:107452. https://doi.org/10.1016/j.cie.2021.107452
160. Jin H, and Xie Y (2023) A review of research on the impact of digitalization on agricultural supply chain security. In Tallón-Ballesteros AJ and Santana-Morales P (Eds.), Digitalization and Management Innovation (pp. 378–385). IOS Press. https://doi.org/10.3233/FAIA230038
161. Ling EK, Wahab SN (2020) Integrity of food supply chain: going beyond food safety and food quality. Int J Prod Qual Manag 29(2):276–295. https://doi.org/10.1504/IJPQM.2020.105963
162. Bui LTC, Carvalho M, Pham HT, Nguyen TTB, Duong ATB, Quang HT (2022) Supply chain quality management 4.0: conceptual and maturity frameworks. Int J Qual Reliab Manag. https://doi.org/10.1108/IJQRM-07-2021-0251
163. Montecchi M, Plangger K, Etter M (2019) It's real, trust me! Establishing supply chain provenance using blockchain. Bus Horiz 62(3):283–293. https://doi.org/10.1016/j.bushor.2019.01.005
164. Luo J, Leng S, Bai Y (2022) Food supply chain safety research trends from 1997 to 2020: a bibliometric analysis. Front Public Health 9:742980. https://doi.org/10.3389/fpubh.2021.742980
165. Pandey V, Pant M, Snášel V (2022) Blockchain technology in food supply chains: review and bibliometric analysis. Technol Soc 69:101954. https://doi.org/10.1016/j.techsoc.2022.101954
166. Fink A (1998) Conducting research literature reviews: from paper to the internet. Sage Publications, Thousand Oaks, CA

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