

Food Industry Sustainability Through Digitalization: A Systematic Review

Kelestarian Industri Makanan Melalui Digitalisasi: Satu Kajian Sistematis

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ABSTRACT

Digitalization is transforming food security by enhancing efficiency, transparency, and sustainability in agriculture. This study systematically reviews the impact of digital technologies such as IoT, AI, and automation, in addressing critical food security challenges, such as supply chain disruptions, resource inefficiencies, and climate risks. A structured methodology, PRISMA, was adopted to collect relevant peer-reviewed literature from 2023 to 2024 across the Scopus and Web of Science databases. After screening 819 publications, 29 studies that met the inclusion criteria were analyzed. Data analysis was conducted using thematic synthesis, where studies were first coded based on predefined criteria aligned with research questions. Open and axial coding techniques were applied to extract patterns, supported by collaborative reviews among authors to ensure consistency and reliability. Five major themes emerged from the synthesis: Emerging Technologies, Digitalization & Sustainability, AI & Automation, Resilience & Optimization, and Knowledge & Innovation. These themes encapsulate how digitalization supports traceability, predictive analytics, and strategic decision-making across the food value chain. Findings indicate that digital technologies improve resource management, reduce food waste, and enhance supply chain resilience. However, barriers such as high implementation costs, data interoperability, and gaps in digital literacy hinder broad adoption. This review highlights the need for robust regulatory frameworks, stakeholder collaboration, and targeted investments in infrastructure and digital skills. Integrating AI-driven forecasting and blockchain-enabled traceability could further strengthen food system sustainability.

Keywords: Food Digitalization; Food Security; Sustainable Agriculture; Agri-Food Transformation, PRISMA Framework

ABSTRAK

Pendigitalan sedang mengubah landskap keterjaminan makanan dengan meningkatkan kecekapan, ketelusan, dan kemampuan dalam sektor pertanian. Kajian ini secara sistematik mengkaji impak teknologi digital seperti Internet of Things (IoT), Kecerdasan Buatan (AI), dan automasi dalam menangani cabaran utama keselamatan makanan, termasuk gangguan rantaian bekalan, ketidakcekapan sumber, dan risiko perubahan iklim. Satu metodologi berstruktur, iaitu PRISMA, telah digunakan untuk mengumpul literatur yang disemak dari tahun 2023 hingga 2024 melalui pangkalan data Scopus dan Web of Science. Daripada 819 penerbitan yang disaring, sebanyak 29 kajian yang memenuhi kriteria pemilihan telah dianalisis. Analisis data dijalankan menggunakan pendekatan sintesis tematik, di mana kajian-kajian ini dikodkan berdasarkan kriteria yang telah ditentukan selaras dengan soalan penyelidikan. Teknik pengkodan terbuka dan paksi telah digunakan untuk mengenal pasti corak berulang, disokong oleh semakan kolaboratif dalam kalangan penulis bagi memastikan konsistensi dan kebolehpercayaan. Lima tema utama telah dikenal pasti daripada sintesis ini: Teknologi Baharu, Digitalisasi & Kelestarian, AI & Automasi, Ketahanan & Pengoptimuman, serta Pengetahuan & Inovasi. Tema-tema ini merangkumi bagaimana pendigitalan menyokong keterkesanan penjejakan, analitik ramalan, dan pembuatan keputusan strategik merentasi rantaian nilai makanan. Penemuan menunjukkan bahawa teknologi digital membantu memperbaiki pengurusan sumber, mengurangkan pembaziran makanan, dan meningkatkan daya tahan rantaian bekalan. Walau bagaimanapun, terdapat halangan seperti kos pelaksanaan yang tinggi, isu keserasian data, dan kekurangan literasi digital yang menghalang penggunaan secara meluas. Kajian ini menekankan keperluan kepada rangka kerja peraturan yang kukuh, kerjasama pelbagai pihak berkepentingan, serta pelaburan yang disasarkan dalam infrastruktur dan kemahiran digital. Integrasi peramalan berasaskan AI dan penjejakan melalui teknologi blockchain berpotensi mengukuhkan lagi kemampuan sistem makanan pada masa hadapan.

Kata Kunci: Pendigitalan Makanan; Keterjaminan Makanan; Pertanian Lestari; Transformasi Agri Makanan; Rangka Kerja PRISMA

INTRODUCTION

Digitalization in food industries is revolutionizing the way food is produced, processed, distributed, and consumed, marking a significant shift towards efficiency, transparency, and sustainability (Khan et al., 2024; Wu, 2024). This transformation is driven by advancements in technology, such as the Internet of Things (IoT), Artificial Intelligence (AI), blockchain, and data analytics, which collectively enable seamless integration and automation across the food value chain (Hasan et al., 2023; Purnama et al., 2023). As the global demand for food grows and securities, digitalization offers innovative solutions to address challenges such as resource optimization, waste reduction, and supply chain resilience. Its relevance extends beyond operational improvements, touching on critical areas such as food safety, traceability, and consumer engagement.

The importance of digitalization in the food industry is underscored by its potential to meet the United Nations' Sustainable Development Goals (SDGs), particularly those related to zero hunger, responsible consumption and production, and climate action (Khan et al., 2024; Wu, 2024; Finger, 2023). For instance, smart farming technologies enable precision agriculture, reducing resource waste while enhancing yield. Similarly, blockchain technology ensures transparent and secure food traceability, addressing food fraud and enhancing consumer trust. AI-driven analytics provide actionable insights for market trends and consumer preferences, enabling companies to align production with demand efficiently. These advancements not only enhance operational efficiency but also foster innovation, competitiveness, and sustainability within the food sector (Somashekar et al., 2024).

Existing research highlights numerous benefits of digitalization in the food industry. Studies have demonstrated how IoT-enabled devices can monitor real-time conditions in agriculture and food storage, reducing losses and ensuring quality (Pushpavalli et al., 2024; Parab, 2024; Abdel Qader, 2023). Blockchain has been widely adopted for enhancing traceability, with noTABLE applications in the seafood and dairy industries to prevent fraud and improve safety (X. Zhang, 2024; Chiaraluce et al., 2024). Meanwhile, AI applications have shown promise in predictive maintenance, quality control, and personalized nutrition (Taneja et al., 2023). Despite these advances, significant disparities exist in the adoption of digital technologies across regions and scales of operation, with smaller food industries often lagging due to resource constraints and lack of expertise (Abdulai et al., 2023).

This review aims to conduct a comprehensive analysis of recent publications on digitalization within the food industries. Guided by the PICO framework (Population, Intervention, Comparison, and Outcomes) (Lockwood et al., 2015), three research questions were developed to address key aspects of this domain as follows:

- RQ1 How can the integration of IoT and blockchain with artificial intelligence and automation enhance the traceability and operational efficiency of food supply chains?
- RQ2 What role does digitalization play in enhancing the resilience and sustainability of food supply chains during global disruptions, such as pandemics or climate-related challenges?
- RQ3 What educational frameworks and innovation strategies are essential to equip the workforce with the digital skills needed for sustainable agri-food system transformation?

LITERATURE REVIEW

The food industry is undergoing a digital revolution, enhancing efficiency, sustainability, and transparency. Technologies like IoT, AI, blockchain, and data analytics are transforming traditional practices (Abdel Qader, 2023; Khamoushi, 2024; Hoque & Padhiary, 2024). IoT sensors optimize farming by monitoring soil conditions, reducing waste (Parab, 2024; Viviane et al., 2023). In the study by Mao et al. (2024) and D. Zhang (2024), they highlighted how AI-driven analytics predict market trends, optimizing production strategies. Zülch et al. (2024) and Tang (2023) emphasize blockchain's role in ensuring food traceability, preventing fraud, and strengthening consumer trust. These innovations are reshaping the food industry, making digitalization a key driver of sustainability and efficiency.

The adoption of digital technologies aligns closely with the United Nations' Sustainable Development Goals (SDGs), particularly those related to zero hunger, sustainable consumption and production, and climate action (Khan et al., 2024; Singh & Jyoti, 2023; Voronkova et al., 2023). Smart farming technologies exemplify this alignment by enabling precision agriculture, which optimizes resource use and improves crop yields while minimizing environmental impact (Hoque & Padhiary, 2024). Blockchain applications in food traceability have been instrumental in combating fraudulent practices in industries such as seafood and dairy, ensuring safety and transparency (Abdel Qader, 2023; X. Zhang, 2024; González Amarillo et al., 2023). AI-driven tools have also shown significant potential in areas like predictive maintenance, quality control, and personalized nutrition, further contributing to operational efficiency and sustainability within the food sector (Taneja et al., 2023; Kaushal, 2024).

Despite these advancements, the adoption of digital technologies in the food industry is uneven, with significant disparities across regions and organizational scales. A qualitative study of smallholders in Selangor, Malaysia, illustrates these disparities. It found that agricultural technologies—such as automated seeding, fertilizing, and harvesting—have been adopted through the theoretical phase of domestication. While this adoption has improved productivity and long-term income, scepticisms and high investment costs continue to hinder the uptake of newer technologies (Othman et al., 2024). Smaller food enterprises and developing economies often lag due to limited access to resources, technological expertise, and financial investment (Diao et al., 2023; Ravshanovich, 2024). Infrastructure gaps further exacerbate these challenges, hindering the scalability and feasibility of digital solutions. Additionally, ethical concerns, such as data privacy and security, remain underexplored, posing significant barriers to widespread adoption (Zampati, 2023; Lei et al., 2022). Addressing these challenges requires a deeper understanding of how socio-economic and technical factors influence the integration of digital technologies.

Existing research has extensively examined the technological applications of digitalization, particularly in enhancing production efficiency and supply chain management. For example, studies by Viviane et al. (2023) and Cerrahoğlu & Cihan (2023) highlighted the use of IoT-enabled devices for monitoring agricultural and storage conditions as well as the deployment of blockchain for traceability (Zülch et al., 2024; Lei et al., 2022; Q. Zhang, 2024), and AI applications for quality control and market analytics (Taneja et al., 2023; Khamoushi, 2024).

Emerging technologies significantly enhance food production and supply chain management. Singh & Raza (2023), propose an IoT-blockchain system integrating MQTT and smart contracts for inventory oversight. Šestak & Copot (2023) highlight an agricultural data ecosystem with trust principles for seamless data sharing. Kuntke et al. (2024) design an offline-capable Farm Management Information System emphasizing privacy and user-friendly interfaces.

Papa et al. (2024) showcase blockchain, IoT, and machine learning for cattle traceability and sustainability, while Ordóñez et al. (2023) underscore blockchain's potential in precision farming, cyber-physical systems, and big data analytics. Despite these advancements, investment costs, privacy issues, and regulatory uncertainties remain pressing concerns.

Kyriakopoulos et al. (2023) highlight digitalization's role in Greek agriculture under the Common Agricultural Policy. McDonagh et al. (2024) stress collaboration and education for sustainability in European food industries. Zorić et al. (2023) emphasize digital solutions to improve food supply chains. Vernooy et al. (2024) advocate digitalization for sustaining community seed banks. Gupta et al. (2023) introduce a framework assessing digital interventions in sustainability. Meanwhile Uyeh et al. (2023) see digitalization as key to boosting African agriculture but note infrastructure challenges.

Artificial intelligence (AI) and automation are transforming food industry operations, enhancing efficiency, security, and sustainability. AI-driven analytics improve state management in agriculture by integrating cybersecurity and environmental monitoring (Kosach et al., 2024). The Fourth Industrial Revolution (4IR) accelerates technological adoption in food and beverage manufacturing, requiring AI-based smart knowledge management for process optimization and workforce skill alignment (Telukdarie et al., 2023). Digitalization in food supply chains strengthens sustainability by addressing inefficiencies using Intuitionistic Fuzzy methodologies for strategic decision-making (Ortiz-Barrios et al., 2023). Hyperspectral imaging (HSI) integrated with AI significantly improves food quality assessment, automating contaminant detection and real-time classification (Nikzadfar et al., 2024). AI-powered machine learning models optimize weather-based agricultural predictions, enhancing soil monitoring and disease forecasting (Diachenko et al., 2024). Large language models (LLMs) offer AI-driven solutions in agricultural consulting and decision support, facilitating modern digital techniques in farming practices (Kuska et al., 2024).

Digitalization enhances food supply chain (FSC) resilience and efficiency, particularly during disruptions like COVID-19. Studies highlight its role in optimizing agrifood supply chains (AFSC) through short supply chains and sensor-based tracking, reducing waste and improving delivery (Granillo-Macías et al., 2024; Schiffmann et al., 2023). Technologies like Blockchain, IoT, and AI improve transparency and automation. Research on the Western Balkans and digital warehousing emphasizes efficiency gains from Automated Guided Vehicles (AGVs) and digital twins (Schiffmann et al., 2023; Alherimi et al., 2024). Digitalization also supports circular economy (CE) efforts by enhancing traceability and reducing waste in grocery retail and agrifirms (Olaghere et al., 2023). Despite benefits, challenges remain in assessing economic returns and sustainability impacts. Future research should integrate cost-benefit analysis and sustainability into digital FSC models (Alherimi et al., 2024).

The food and agricultural sectors can be reshaping thru the digitalization as well as enhancing efficiency and collaboration. The FOODSAFETY4EU project highlighted the benefits and challenges in virtual social lab process (Schrammel & Marschalek, 2024). Similarly, the Agricultural Knowledge and Innovation Systems (AKIS) study emphasized knowledge management as key to adapting to digital change (Charatsari, Michailidis, et al., 2024). Research on agricultural social networks also stressed the role of digital solutions in sustaining value chains (Tombe & Smuts, 2023). Technology adoption drives agribusiness growth, with factors like credit access, education, and management support playing critical roles (Kitole et al., 2024; Calafat-Marzal et al., 2023). However, Agriculture 4.0 technologies such as AI and IoT have widened digital disparities, raising ethical concerns (Bampasidou et al., 2024). Blockchain adoption remains

limited, requiring better stakeholder engagement to bridge the digital divide (Charatsari, Michailidis, et al., 2024).

The integration of emerging technologies, AI, and automation is transforming the food industry, enhancing efficiency and sustainability. Digitalization supports sustainable practices by optimizing resource use and reducing environmental impact. AI and automation streamline operations, improving productivity and decision-making. Resilience is strengthened through digital solutions that enhance adaptability and supply chain optimization. Knowledge and innovation play a pivotal role in driving technological advancements, fostering collaboration, and ensuring continuous improvement. The interplay of these themes underscores the necessity of a balanced approach, where innovation, sustainability, and resilience collectively contribute to the long-term success of the food industry's digital transformation.

MATERIAL AND METHODS

This review paper follows the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Page et al., 2021). PRISMA is a widely recognized methodology for improving the rigor of systematic reviews, involving four key stages; Preliminary Identification, Screening, Eligibility, and Inclusion (Figure 1). The Preliminary Identification stage focuses on locating relevant articles to the research objectives using predefined search keywords across selected databases. During the Screening stage, earlier findings are filtered based on specific criteria to eliminate those that do not meet the research scope. The Eligibility phase involves a detailed examination of titles, abstracts, and full texts to ensure alignment with the inclusion criteria, such as field relevance and scope. Finally, the Inclusion phase involves extracting pertinent information from the selected studies, including key characteristics, methodologies, findings, and other relevant details to address the research questions effectively.

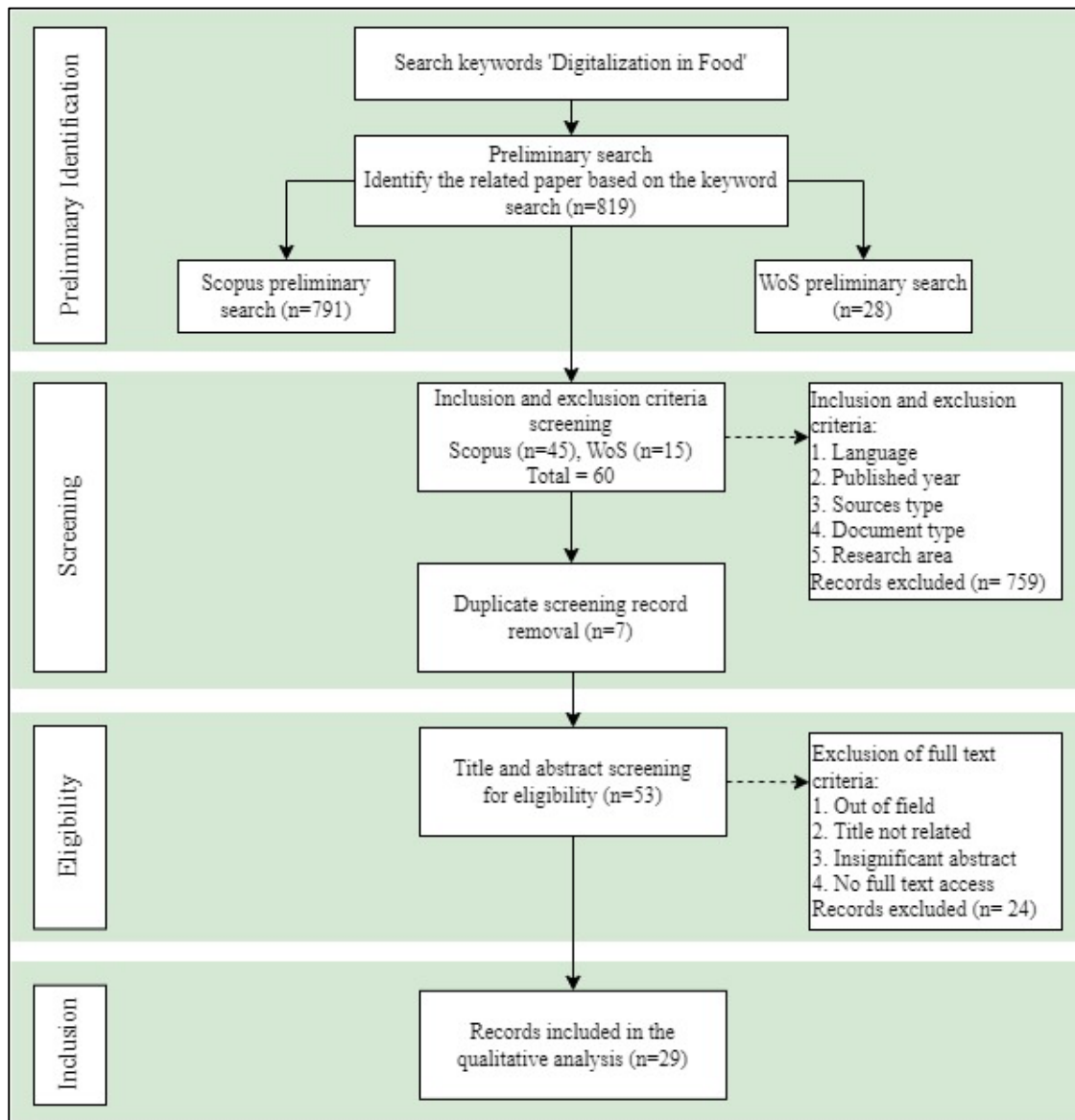


FIGURE 1. The Implementation flow of the PRISMA Process (Page et al., 2021)

SCREENING

During the screening stage, potentially relevant research items were evaluated to ensure they align with the predefined research question(s). This stage often involves selecting research items based on the digitalization in food industries. This stage also removing the duplicate papers found. Initially, 759 publications were excluded, ultimately focusing on 60 papers that met the criteria (see TABLE 1). The first criterion was literature, as it is the main source of practical recommendations, including reviews, meta-syntheses, meta-analyses, books, book series, chapters, and conference proceedings not covered in the most recent study. This review was limited to English language publications from 2023 to 2025. At the end, seven publications were rejected due to duplication.

TABLE 1. The selection criterion in Screening stage

Criterion	Language	Timeline	Literature type	Publication Stage	Subject
Inclusion	English	2023-2025	Journal (Article)	Final	Computer Science Others
Exclusion	Others	<2023	Conference, Book, Review	In Press	

ELIGIBILITY

In the eligibility stage, 53 articles were evaluated for review. After a thorough examination of their titles and key content, 24 articles were excluded due to being outside the relevant field, having insignificant titles, irrelevant abstracts, or lacking full-text access. Consequently, 29 high-quality articles were left for the upcoming review.

DATA ABSTRACTION AND ANALYSIS

An integrative thematic analysis was employed to systematically extract and synthesize data from the 29 eligible studies identified through the PRISMA framework. Each article was first coded using a predefined coding structure aligned with the research questions (RQ1–RQ3), with emphasis on technological application, sustainability impact, and implementation challenges. NVivo 14 was used to aid qualitative coding and ensure data consistency.

A two-stage analytical approach was adopted. In the first stage, open coding was applied to identify recurring concepts, keywords, and methodologies across studies. These initial codes were then clustered into thematic categories using axial coding, with input and validation from all co-authors. In the second stage, thematic synthesis was conducted, organizing the findings into five themes: Emerging Technologies, Digitalization & Sustainability, AI & Automation, Resilience & Optimization, and Knowledge & Innovation.

Inter-coder reliability was ensured through consensus meetings, where discrepancies in thematic categorization were resolved. To enhance validity, the final themes were cross-referenced with the study's research questions and were aligned with the SDGs where applicable. This rigorous analytical process allowed for a structured interpretation of the literature and ensured that the findings reflected both depth and breadth in the field of food industry digitalization.

RESULTS AND DISCUSSION

A total of 29 articles were extracted and examined based on the search methodology. These studies employed various research approaches, including quantitative, qualitative, and mixed-mode methods, and originated from diverse countries such as the India, Ukraine, Tanzania, South Africa, USA, UAE and several European nations and Balkan Countries. Five primary themes were identified: Emerging Technologies, Digitalization & Sustainability, Artificial Intelligence (AI) & Automation, Resilience & Optimization, and Knowledge & Innovation. These themes reflect the global efforts in leveraging digital technologies to enhance food security, optimize agricultural processes, and promote sustainable practices across different regions (refer TABLE 2).

TABLE 2. Theme Analysis

Author	Title	Approach	Theme	Country of Origin
Alherimi et al.	A Systematic Review of Optimization Approaches Employed in Digital Warehousing Transformation	Quantitative	Resilience and Optimization	UAE
Bampasidou et al.	Overcoming 'Digital Divides': Leveraging higher education to develop next generation digital agriculture professionals	Qualitative	Knowledge and Innovation	USA
Calafat-Marzal et al.	Agri-food 4.0: Drivers and links to innovation and eco-innovation	Quantitative	Knowledge and Innovation	Spain
Charatsari, et al.	Do Agricultural Knowledge and Innovation Systems Have the Dynamic Capabilities to Guide the Digital Transition of Short Food Supply Chains?	Qualitative	Knowledge and Innovation	Greece/Italy
Diachenko et al.	An Improved Approach to Prediction of Maize Disease Occurrence Based on Weather Monitoring and Machine Learning: Case of the Forest-Steppe and Northern Steppe of Ukraine	Quantitative	AI and Automation	Ukraine
Granillo-Macías et al.	Reconfiguration of Agrifood Supply Chain Management in Latin America during COVID-19: A Brief Literature Review	Qualitative	Resilience and Optimization	Mexico
Gupta et al.	Operationalizing Digitainability: Encouraging Mindfulness to Harness the Power of Digitalization for Sustainable Development	Mixed Mode	Digitalization and Sustainability	Germany
Kitole et al.	Digitalization and agricultural transformation in developing countries: Empirical evidence from Tanzania agriculture sector	Quantitative	Knowledge and Innovation	Tanzania
Kosach et al.	Artificial Intelligence in The Mechanism of State Management of The Development of The Regional Agrarian Sector in The Context of The National Security	Quantitative	AI and Automation	Ukraine
Kuntke et al.	GeoBox: design and evaluation of a tool for resilient and decentralised data management in agriculture	Qualitative	Emerging Technologies	Germany
Kuska et al.	AI for crop production - Where can large language models (LLMs) provide substantial value?	Qualitative	AI and Automation	Germany
Kyriakopoulos et al.	Benefits and Synergies in Addressing Climate Change via the Implementation of the Common Agricultural Policy in Greece	Qualitative	Digitalization and Sustainability	Greece
Marić et al.	Analysis of Food Supply Chain Digitalization Opportunities in the Function of Sustainability of Food Placement in the Western Balkans Region	Quantitative	Resilience and Optimization	Serbia
McDonagh et al.	An Exploration of Food Sustainability Practices in the Food Industry across Europe	Qualitative	Emerging Technology, Digitalization and Sustainability	Europe
Nikzadfar et al.	Hyperspectral Imaging Aiding Artificial Intelligence: A Reliable Approach for Food Qualification and Safety	Qualitative	AI and Automation	Italy
Olaghere et al.	The Implications of Digitalization in Retail Service Delivery on Circular Economy in Nigeria: An Exploratory Case Study	Qualitative	Resilience and Optimization	Nigeria
Ordóñez et al.	Blockchain in Agriculture: A PESTELS Analysis	Quantitative	Emerging Technologies	Spain

Ortíz-Barrios et al.	A novel approach integrating IF-AHP, IF-DEMATEL and CoCoSo methods for sustainability management in food digital manufacturing supply chain systems	Mixed Mode	AI and Automation	Colombia
Papa et al.	Technologies in cattle traceability: A bibliometric analysis	Quantitative	Emerging Technologies	Brazil
Schiffmann et al.	A Cost–Benefit Analysis Simulation for the Digitalisation of Cold Supply Chains	Quantitative	Resilience and Optimization	UK
Schrammel et al.	Virtual Social Labs – Requirements and Challenges for Effective Team Collaboration	Qualitative	Knowledge and Innovation	Austria
Singh et al.	A framework for IoT and blockchain based smart food chain management system	Quantitative	Emerging Technologies	India
Šestak et al.	Towards Trusted Data Sharing and Exchange in Agro-Food Supply Chains: Design Principles for Agricultural Data Spaces	Qualitative	Emerging Technologies	Slovenia
Telukdarie et al.	Industry 4.0 Technological Advancement in the Food and Beverage Manufacturing Industry in South Africa—Bibliometric Analysis via Natural Language Processing	Mixed Mode	AI and Automation	South Africa
Tombe & Smuts	Agricultural Social Networks: An Agricultural Value Chain-Based Digitalization Framework for an Inclusive Digital Economy	Qualitative	Knowledge and Innovation	South Africa
Uyeh et al.	Perspectives on the strategic importance of digitalization for Modernizing African Agriculture	Qualitative	Digitalization and Sustainability	USA
Vernooy et al.	Promising Strategies to Enhance the Sustainability of Community Seed Banks	Qualitative	Emerging Technology, Digitalization and Sustainability	Netherland
Yadav et al.	Exploring the relationship between digitalization, resilient agri-food supply chain management practices and firm performance	Quantitative	Resilience and Optimization	India
Zorić et al.	The Importance of Digitalization for the Sustainability of the Food Supply Chain	Quantitative	Digitalization and Sustainability	Serbia

EMERGING TECHNOLOGIES

The digitalization of food supply chains, leveraging IoT, blockchain, and emerging technologies, has advanced significantly in recent years. McDonagh et al. (2024) introduced a framework combining IoT and blockchain to enhance smart food chain management. Their study focuses on regulating food inventory systems to ensure quality and safety, utilizing MQTT servers to log geolocation, temperature, and movement data from IoT sensors. They demonstrate how smart contracts can efficiently manage custody and shipment tracking, reducing fraud and food spoilage. However, the study highlights the complexity and high costs of implementation, which pose barriers to widespread adoption, particularly in small and medium-sized enterprises (SMEs). Additionally, integration challenges between legacy systems and blockchain networks require further refinement to improve interoperability.

Similarly, (Vernooy et al. (2024) and (Šestak & Copot (2023) emphasize the need for trusted data sharing in agro-food supply chains. They propose Agricultural Data Spaces (ADS) to address challenges like stakeholder mistrust, inadequate data access policies, and ambiguous data ownership. ADS aims to foster collaboration and create sustainable agricultural ecosystems by ensuring secure and transparent data exchanges. (Šestak & Copot, 2023) further highlight that the establishment of Agricultural Data Ecosystems (ADE) requires overcoming socioeconomic and technological challenges, particularly those related to interoperability and governance structures. Their study reviews 27 scientific works, identifying key barriers such as inadequate data-sharing policies and unclear ownership agreements. Without clear governance frameworks and technical interoperability solutions, ADS implementation may struggle to gain traction, especially in regions with weak digital infrastructure.

The role of decentralized systems in agriculture is further explored by Kuntke et al. (2024), who developed GeoBox, a resilient Farm Management Information System (FMIS). Designed to function offline and address privacy concerns, GeoBox provides a simplified user interface that ensures data reliability even in remote agricultural regions. Its ability to store and manage farm-related data securely allows farmers to make more informed decisions. However, gaps remain in addressing the broader scalability of decentralized systems, especially in resource-limited settings where digital adoption is slower. The need for cost-effective solutions tailored to different agricultural environments remains a key challenge.

Singh & Raza (2023) propose a framework for IoT and blockchain-based smart food chain management systems (IBFS). Their study focuses on regulating food inventory systems in organizations, ensuring food safety and quality through an IoT-enabled blockchain architecture with smart contracts. The framework integrates MQTT servers to log geolocation, movement, and temperature data from IoT sensors. Using Ethereum-based blockchain technology, the system employs two types of smart contracts: one for custody and another for shipment tracking. Performance evaluation of IBFS in terms of gas cost under various test conditions demonstrates the framework's effectiveness. However, challenges include the high costs of blockchain implementation and interoperability issues with existing food supply chain infrastructures.

Blockchain technology has been pivotal in advancing agricultural traceability. Papa et al. (2024) analyze its application in cattle traceability, highlighting its potential to mitigate environmental impacts through authenticated data systems. They note that IoT, machine learning, and blockchain can enhance transparency and accountability, but challenges like high costs, interoperability issues, and privacy concerns limit adoption. Regulatory inconsistencies also create hurdles, as varying national and international standards complicate blockchain implementation across borders. These findings align with Ordóñez et al. (2023), who explored blockchain's role in agriculture using the PESTELS framework, identifying critical technological, economic, and regulatory challenges that hinder large-scale adoption.

The convergence of IoT, blockchain, and AI offers transformative solutions for sustainability, transparency, and efficiency in food supply chains. Real-time monitoring and predictive analytics allow for better resource allocation, reducing food waste and optimizing logistics. However, persistent obstacles include high implementation costs, insufficient data-sharing mechanisms, and a lack of digital literacy among stakeholders. Addressing these issues requires standardizing protocols, fostering interdisciplinary collaboration, and investing in scalable solutions that cater to both large agribusinesses and smallholder farmers. Future research should explore policy frameworks, subsidy models, and public-private partnerships that could drive digital adoption while ensuring inclusivity and sustainability in the food industry.

DIGITALIZATION AND SUSTAINABILITY

Digitalization in the agri-food sector has emerged as a pivotal strategy to address sustainability challenges. Various researchers have explored its multifaceted applications, discussing its implications for policy frameworks, supply chain efficiency, community initiatives, and the alignment with global sustainability goals. Kyriakopoulos et al. (2023) provided a comprehensive analysis of how Greece's agricultural sector can adapt to climate change through the Common Agricultural Policy (CAP) 2023–2027. Their findings emphasize the need for targeted actions such as education, consulting services, and coupling innovation with digitalization to address risks related to climate change and environmental degradation. Similarly, McDonagh et al. (2024) explored sustainability practices in Europe's food industry, highlighting challenges such as cost, employee engagement, and monitoring time. The study advocates for collaboration among companies to share sustainability data and enhance awareness. This discourse by operationalizing the concept of "digitainability," introducing a framework for assessing digital interventions and their alignment with Sustainable Development Goals (SDGs) (Gupta et al., 2023).

The role of digitalization in enhancing the sustainability of food supply chains (FSCs) has been a focal point of recent studies. Past researcher has identified key indicators such as poor coordination, food loss, and transaction costs as barriers to FSC sustainability (Zorić et al., 2023). Their proposed measures include digitalizing business processes to improve coordination and control. It then further elaborated on the potential of digital tools like blockchain and AI to transform FSC operations, aligning them with long-term sustainability goals. These studies collectively underscore the importance of digitalization in addressing inefficiencies and fostering resilience in food systems.

Vernooy et al. (2024) examined community seed banks—farmer-managed organizations dedicated to conserving crop diversity. Their research identified strategies like networking, digitalization, and partnerships with national genebanks as critical for the sustainability of these initiatives. Uyeh et al. (2023) provided complementary insights, discussing how digital tools can modernize African agriculture by enhancing productivity, food security, and climate resilience. Both studies emphasize the role of localized efforts supported by digital innovation in achieving broader sustainability objectives.

Despite its transformative potential, digitalization poses several challenges. Issues like environmental degradation and inequality, advocating for a holistic impact assessment framework (Gupta et al., 2023). Uyeh et al. (2023) identified infrastructural and expertise gaps as significant barriers, suggesting public-private partnerships as a solution. The proliferation of environmental labels and the need for standardized metrics to evaluate sustainability practices must be pointed out (McDonagh et al., 2024). Addressing these challenges requires a concerted effort from stakeholders across the agri-food sector. The integration of digitalization into agri-food systems offers promising pathways to enhance sustainability. From policy frameworks and supply chain efficiency to community initiatives, digital tools have the potential to drive significant improvements. However, realizing this potential necessitates overcoming challenges related to cost, infrastructure, and stakeholder collaboration. Future research should focus on refining digital tools and frameworks to align with global sustainability goals.

ARTIFICIAL INTELLIGENCE AND AUTOMATION

The integration of AI and automation in food industries has become a significant focus of research, with various studies exploring its transformative impact on different aspects of the sector. The findings from recent studies highlight diverse applications and methodologies, offering valuable insights into how AI and automation are shaping the food industry. The role of AI in enhancing state management mechanisms within the regional agrarian sector, particularly in addressing challenges related to food security and environmental risks (Kosach et al., 2024). Integrating AI—such as data analytics and machine learning—into public administration enhances threat detection and risk prevention. The study proposes a two-pronged strategy: bolster cyber and environmental security at the enterprise level and incorporate AI into regional agriculture for greater resilience and sustainability.

Similarly, Telukdarie et al. (2023) discuss the implementation of Industry 4.0 technologies in the food and beverage manufacturing sector in South Africa. Technology selection and skill identification face challenges amid rapid evolution. Adopting smart knowledge management and NLP for bibliometric analysis enables efficient data extraction, offering a framework to optimize manufacturing and address global competition in the food industry.

An integrated method for sustainability management in digital manufacturing supply chain systems (DMSCS) within the food industry has been introduced (Ortíz-Barrios et al., 2023). Their approach uses IF-AHP, IF-DEMATEL, and CoCoSo methods to address inefficiencies in food supply chains. The study highlights location and manufacturing capacity as key drivers of sustainability, showing its effectiveness in enhancing sustainability and efficiency in the pork supply chain.

Nikzadfar et al. (2024) focus on the application of hyperspectral imaging (HSI) combined with AI for food quality and safety assessment. HSI non-destructively detects contaminants by analyzing spectral signatures of food components. Integrating machine learning enhances feature extraction and classification, enabling automated inspection, reduced errors, and real-time decisions that significantly improve food safety and quality assurance. The use of machine learning algorithms for predicting maize disease occurrences based on weather monitoring in Ukraine (Diachenko et al., 2024). Random Forest emerges as the top predictive algorithm, enabling software for soil and climate monitoring. Integrating expert knowledge with low-level data processing yields a robust framework that improves agricultural efficiency and bolsters food security by mitigating crop disease risks.

Kuska et al. (2024) delve into the potential applications of large language models (LLMs) like ChatGPT in agricultural tasks. Their research explores how LLMs can assist with plant disease decision support, technical content creation, and digital techniques in agriculture. Despite limitations, the study pinpoints areas where LLMs streamline processes, improve research efficiency, and enhance knowledge sharing, offering a roadmap for applying LLMs in crop production and management. By addressing challenges related to sustainability, quality assurance, predictive analytics, and knowledge management, these technologies are paving the way for more efficient and resilient food systems. The integration of AI-driven methodologies not only enhances operational efficiency but also contributes to broader goals of food security and environmental sustainability.

RESILIENCE AND OPTIMIZATION

The literature demonstrates how digitalization bolsters resilience, optimization, and sustainability in food supply chains. Granillo-Macías et al. (2024) emphasize short supply chains and e-commerce as pivotal for managing disruptions in Latin America, particularly in response to fluctuating consumer demands and supply chain shocks. Meanwhile, Marić et al. (2024) highlight how Blockchain, IoT, and AI are revolutionizing the food industry in the Western Balkans by improving traceability, reducing inefficiencies, and ensuring sustainable operations. Yadav et al. (2024) further confirm that IoT-based solutions enhance organizational integration, leading to improved coordination, inventory accuracy, and overall performance.

Studies on optimization underscore digital technologies' capacity to reduce waste and costs while improving efficiency. Schiffmann et al. (2023) reveal how cold chain digitalization significantly minimizes product loss, shortens delivery distances, and optimizes transportation routes through data-driven logistics. Similarly, Alherimi et al. (2024) demonstrate that digital twins and automated guided vehicles (AGVs) improve warehousing efficiency by streamlining inventory tracking and predictive maintenance. Yadav et al. (2024) further link data-driven practices to enhanced decision-making processes, reinforcing the importance of analytics in achieving supply chain optimization. Additionally, Marić et al. (2024) and Olaghere et al. (2023) connect digitalization to sustainable initiatives such as waste reduction, circular economy models, and short supply chains, which collectively reduce environmental impact and improve resource efficiency. Nevertheless, significant challenges remain. Alherimi et al. (2024) stress the absence of economic analyses, such as return on investment (ROI) evaluations, and standardized sustainability metrics, which hinder widespread adoption. Schiffmann et al. (2023) highlight the need for broader qualitative assessments to understand digitalization's impact on small-scale producers. Yadav et al. (2024) recommend advanced tagging technologies and real-time analytics to enhance transparency and decision-making. While digitalization undeniably strengthens resilience and sustainability in food supply chains, further research is required to improve its economic feasibility, adaptability, and long-term impact in diverse agricultural contexts.

KNOWLEDGE AND INNOVATION

The transformation of the agri-food sector through digitalization has been explored from various angles, with a shared emphasis on the interplay between knowledge, innovation, and education. Key themes include the role of digital infrastructure, innovative practices, stakeholder engagement, and capacity-building initiatives.

The adoption of digital technologies across the agri-food value chain is propelled by both internal and external drivers. Calafat-Marzal et al. (2023) identified management support and competitive pressures as pivotal in encouraging digital adoption within agri-food companies. Their research highlighted the role of technologies like IoT, big data, and artificial intelligence in enhancing competitiveness and promoting sustainability-oriented innovations. Similarly, Kitole et al. (2024) emphasized the role of access to credit, extension services, and education in driving digital adoption among Tanzanian smallholder farmers. These findings align with the conclusions of Tombe & Smuts (2023), who developed a framework demonstrating the potential of agricultural social networks in facilitating the digitalization of value chains. These networks integrate stakeholders such as farmers, distributors, and retailers, underscoring the necessity of collaboration and innovation for sustainable digital transitions.

The complexity of digitalization processes often poses significant challenges, particularly in ensuring effective stakeholder engagement. Charatsari, Lioutas, et al. (2024) analyzed Agricultural Knowledge and Innovation Systems (AKISs) in Greece and Italy, revealing the importance of dynamic capabilities—such as sensing, seizing, and adapting to opportunities—to foster digital transitions. However, their findings indicated a need for improved connectivity and resource-sharing among stakeholders, particularly public advisory organizations and universities, to build a robust knowledge base. Schrammel & Marschalek (2024) provided further insights into stakeholder dynamics, focusing on virtual collaborations in social labs addressing food safety. While virtual engagements facilitated broader participation, they also encountered technical challenges and issues of role accountability, emphasizing the need for adaptive strategies in virtual collaboration environments. Bridging knowledge and skill gaps in digital agriculture is critical to addressing the sector's workforce development challenges. Bampasidou et al. (2024) argued that higher education and extension programs play a pivotal role in mitigating socioeconomic disparities exacerbated by digital technologies. Their study underscored the importance of upskilling and reskilling agricultural professionals to equip them with AI, robotics, and IoT competencies. Additionally, integrating ethical considerations into technological advancements is essential for equitable digital transformations. These findings resonate with the observations of Kitole et al. (2024), who advocated for the inclusion of digital literacy in educational initiatives and the strategic promotion of public-private partnerships to enhance accessibility and inclusivity.

Digital technologies not only drive innovation but also reinforce sustainability within the agri-food sector. According to Calafat-Marzal et al. (2023), companies that actively adopt advanced digital tools tend to implement more eco-innovative practices, thereby enhancing their sustainability credentials. Similarly, Tombe & Smuts (2023) proposed a resilience-based framework for digitalizing agricultural value chains, emphasizing sustainability as a core principle. These studies highlight the intertwined nature of innovation and eco-innovation, suggesting that digitalization can simultaneously address economic and environmental objectives. The literature underscores the transformative potential of digitalization in the agri-food sector, facilitated by robust stakeholder collaboration, targeted educational initiatives, and innovative frameworks. Effective implementation requires addressing challenges related to resource-sharing, stakeholder engagement, and workforce development. Future efforts should focus on fostering inclusivity and sustainability to ensure that digital advancements benefit all actors within the agri-food ecosystem.

CONCLUSION

The integration of emerging technologies, digitalization, AI, and automation is driving a significant transformation in the food industry, enhancing efficiency, sustainability, and resilience. Technologies such as IoT, blockchain, and AI contribute to improved transparency and supply chain management. However, widespread adoption is challenged by high implementation costs, limited interoperability, and data privacy concerns. Digitalization plays a strategic role in promoting sustainability by addressing operational inefficiencies and supporting alignment with global environmental objectives. AI and automation further optimize production processes through predictive analytics, real-time monitoring, and data-driven decision-making, thereby strengthening food security. Efforts to enhance resilience and optimization are evident in the application of digital tools like digital twins, blockchain, and IoT, which support waste reduction, cost-efficiency, and logistics improvement. Nonetheless, economic feasibility and adaptability issues remain

pressing concerns. The role of knowledge and innovation is central in this transformation, particularly through education, stakeholder collaboration, and skill development. Bridging digital literacy gaps and strengthening institutional support are key enablers for inclusive technology adoption. To move forward, it is essential to establish standardized frameworks, encourage public-private partnerships, and invest in sustainable infrastructure. Clear regulatory policies and collaborative strategies must be prioritized to build trust and ensure ethical deployment of technologies. Future research should focus on scalable, economically viable models that integrate social and environmental considerations. By addressing these multidimensional challenges, the food industry can achieve a robust, inclusive, and sustainable digital ecosystem.

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