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Recent advances in the use of digital technologies in agri-food processing: A short review

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ABSTRACT

This review provides an overview of recent advances in the use of digital technologies in agri-food processing. With the increasing demand for food, the agri-food industry must produce more food with fewer resources while also addressing sustainability concerns. Digital technologies, such as the Internet of Things, artificial intelligence, blockchain, and robotics, are transforming the way food is produced, processed, and distributed. These technologies offer several benefits, including increased efficiency, improved product quality and safety, reduced waste, and environmental sustainability. Digital technologies enable real-time monitoring of critical parameters, such as temperature, pH, and moisture, which can help prevent spoilage, reduce food waste, and ensure that safe and high-quality food reaches consumers. The review covers the challenges and opportunities for the wider adoption of digital technologies in the sector, as well as potential future developments. The industry has the potential to undergo a revolutionary transformation and tackle significant challenges by embracing digital technologies.

1. Introduction

The agri-food industry is a complex, integrated production chain that spans from primary agriculture to the mature food and beverage sectors. This approach, known as "field to fork" (F2F), is considered one of the world's most important sectors, contributing significantly to the economic progress of nations and having a major social impact.

This industry is strong and complex, presenting a wide range of process and operational challenges (Panetto et al., 2020). To improve agricultural production and product quality, and to satisfy the market demands of an ever-growing population, the agri-food industry must develop innovative and sustainable solutions. As with all industries, technology plays a key role in agri-food operations and decision-making.

The agricultural sector is undergoing a digital revolution. Computers are now used in all agriculture-related processes, from machinery to decision-making systems, through the use of robots, sensors and cyber-physical systems technologies. By using integrated decision-support systems in conjunction with advanced internet networks and services, the agri-food sector has great potential for radical improvement in terms of intelligence, efficiency, sustainability and performance. This potential is particularly relevant when considering the digital agri-food approach, which accelerates and supports agriculture in terms of sustainability, land management, quality of life and competitiveness (Panetto et al., 2020).

For example, data-gathering or collection devices, such as drones and sensors, can be combined with Internet of Things (IoT) technologies. These devices can communicate with decision-support software to inform agricultural stakeholders and contribute to field management (Glaros et al., 2023). This enable effective control of where and how to apply pest or weed control strategies, harvest, or water (Fountas et al., 2020; Glaros et al., 2023).

The agri-food sector presents numerous opportunities for designing

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the Internet of the Future, from the physical layer to the service layer, transforming data into first-class entities (Panetto et al., 2020). The use of digital technologies, such as the Internet of Things (IoT), Big Data, artificial intelligence (AI) and blockchain technologies, offers new opportunities to address challenges in the industry. These technologies are changing the way companies do business, as they affect operational routines and create new ways of networking with customers, suppliers and stakeholders (Cheng & Wang, 2021; Ancín et al., 2022).

In simpler terms, the use of digital technologies in agri-food aims to address sustainable challenges by increasing revenues and reducing the pressure on agri-food supply chain actors. These actors face complex, external factors beyond their control (like weather conditions, market behaviors, and policies), but digital technologies can help them react in time by visualizing current trends in needs. This article reviews over 75 articles and presents recent digital technologies developed to improve the agri-food industry.

To accomplish this, a literature review methodology was used. Firstly, keywords related to agri-food industries were identified. Then, recent publications (less than five years) were focused on, and linked publications and data-based repository were searched. The structure of this paper is as follows: firstly, an overview of digital technologies in agri-food industries has been developed. Secondly, recent advances in this domain have been discussed. The third section presents digital technologies for improving efficiency and sustainability in agri-food processing industries. The fourth section focuses on case studies of digital applications used in agri-food processing. Lastly, the fifth section highlights projections for digital technologies in the agri-food industries.

2. Digital technologies in agri-food processing: an overview

2.1. Digital technologies and their relevance to agri-food processing

Digital technologies are electronic tools, systems, devices, and resources capable of generating, storing, or processing data. This includes software applications, hardware devices, and communication networks that enable data to be processed, stored and transferred.

In agriculture, terms like "digital agriculture", "agriculture 4 0" and "digital agricultural revolution" are used to describe an approach aimed at making food production more efficient. All these names refer to an approach aimed at making food production more efficient. This efficiency is achieved through streamlined communication of high-quality data and the use of current technologies (e.g. Internet of Things, Big Data, artificial intelligence, cloud computing, remote sensing, etc.). Optimization of food systems can achieve social, environmental, and economic goals, such as increased production yields, improved nutritional quality of food products, greater transparency, improved animal welfare, and greener production.

While all definitions focus on the potential of digital tools to increase agronomic/production efficiency, many emphasize the impact on value chains, including e-commerce technology. This technology improves market access, restructures value chains and directly connects consumers and producers. However, it also presents challenges, such as the increased concentration of market power in the hands of a few selected platforms (Bahn et al., 2021; Glaros et al., 2023).

2.2. Different types of digital technologies used in agri-food processing

There are several types of digital technology used in agri-food processing, such as artificial intelligence, the Internet of Things, blockchain, Big Data, robotics and smart sensors (refer to Fig. 1). These technologies can be used by the entire supply chain, from farm or field to the fork (F2F). The main objective of these technologies is to improve productivity, reduce food safety risks, and enhance the sustainability of the entire supply chain.

2.3. Artificial intelligence (AI)

AI refers to the ability of machines to acquire knowledge and make informed decisions by processing data. It encompasses a set of technologies based on electronic devices, computer systems, and robots that enhance and improve the acuity, speed, accuracy and efficiency of the user's activity (Ben Ayed & Hanana, 2021). The primary goal of AI is to

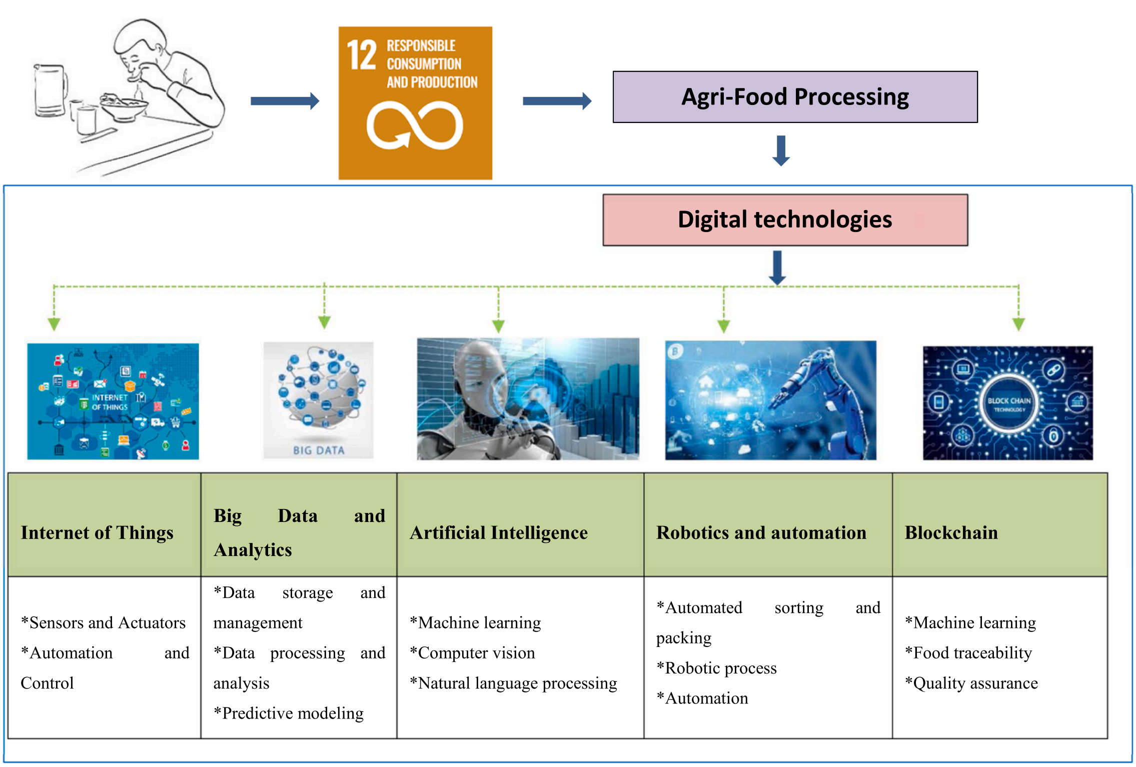

Fig. 1. Overview of various digital technologies used in agri-food processing.

make computers, machines or robots intelligent, akin to human thought. In the realm of technology, AI should be able to easily identify things, recognize objects, analyze profiles, find solutions, make decisions, order actions, predict anomalies and learn and remember the next steps in the supply chain (Ben Ayed et al., 2022; Hassoun et al., 2022).

In agri-food processing, AI can be used to automate tasks such as sorting, grading and packaging produce, forecasting crop yields and detecting food safety risks. It can also be employed to mitigate risk factors, improve food security and achieve self-sufficiency, while reducing poverty, minimizing hunger, and preserving natural resources. Emerging technologies based on artificial intelligence can help increase the productivity and efficiency in the food supply chain while enhancing agriculture and preserving biodiversity (Lezochea et al., 2020; Ben Ayed et al., 2022).

2.4. Internet of Things (IoT)

IoT refers to the integration of sensors and actuators within physical objects, enabling their connection through wired and wireless networks, often utilizing the same Internet Protocol used by the Internet. In 2021, the IoT market stood at $385 billion and is forecast to reach over $2.4 trillion by 2029 (Insights, 2021). The concept is to connect devices and sensors to the Internet to collect data and automate processes (Colizzi et al., 2020; Ben Ayed et al., 2022).

The integration of IoT platforms in agriculture, also known as "precision agriculture" or "smart agriculture", provides additional data sources describing agricultural features, such as water, soil, humans and animals, with more data (Colizzi et al., 2020). However, the increasing focus on IoT in recent research emphasizes the proliferation of IoT platforms. This expansion generates new implementation frameworks addressing different requirement models, new heterogeneous components and sensor networks with different monitoring models, temporal processing patterns, and unbalanced energy consumption. Incorporating IoT platforms into agricultural practices presents notable research challenges, particularly regarding the interoperability of data storage and utilization in the cloud (protocols, security, etc.), performance monitoring, etc. (Lezochea et al., 2020). Moreover, the end user must participate in training sessions to learn and understand the use and applicability of the technology (Ben Ayed et al., 2022).

Most IoT applications of digital technologies in the agri-food industry focus on monitoring temperature, traceability, humidity, color, and improving sustainability performance (Endres et al., 2022). Applications of this nature hold significant importance within the vegetable supply chain, specifically during the agricultural phase. This stage necessitates precise monitoring of indicators to improve crop productivity. IoT systems have proven instrumental in optimizing operational parameters, including pesticide and water usage (Moysiadis et al., 2021; Hassoun et al., 2022). Other parameters can be monitored via IoT, such as soil composition, humidity, temperature, and crop physiology, which can provide information for more accurate crop monitoring (Maraveas & Bartzanas, 2021; Hassoun et al., 2022; Karmakar et al., 2022).

2.5. Blockchain

Blockchain is a transparent digital ledger technology that records transactions and stores data in a secure and decentralized way. It was developed in 2009 and has three different types: open blockchain, private blockchain, and hybrid blockchain (Ben Ayed et al., 2022). The application of this technology in the agri-food supply chain has gradually extended due to its benefits in ensuring food traceability, transparency, safety, and security (Ben Ayed et al., 2022). It provides an innovative solution for these issues in the sector.

2.6. Big data (BD) technologies

BD refers to large, fast-moving and complex data that cannot be processed and managed by conventional and traditional techniques (Hassoun et al., 2022). It applies to data that is so vast, diverse and rapidly changing that conventional technologies, tools, and systems are unable to handle it effectively. The technology is characterized by its five "Vs" (volume, velocity, variety, veracity and value), which make it a vast enterprise (Belaud et al., 2019). These five "Vs" refer to the large volumes of low-density unstructured data, the rapid speed at which data is received and exploited, the variety of availability of many types of data, the level of confidence and quality of the data, and finally, the detection of exploited values from the DB to support decision-making (Belaud et al., 2019; Ben Ayed et al., 2022).

The integration of BD technologies in agri-food projects holds significant importance in three key areas: i) the extension of farmers' data to generate new knowledge; ii) the creation of innovative services and processes by IT providers and software developers and iii) the extension and adaptation of BD models linked to ICT and Factories of the Future (FoF) for agriculture. Numerous Big Data Repositories presently exist that ensure accessibility and utilization of Agri-Food data. For example, the "National Climatic Data centre" (around 2.9 GB per day); satellite imagery and metrological information from Google and NASAEarth Exchange; soil, water, and geospatial data from the National Resources Conservation Service (USA); OpenCorporates, etc. (Lezochea et al., 2020; Ben Ayed et al., 2022).

2.7. Knowledge model approaches

The objective of developing valuable knowledge models in agriculture is to utilize diverse data repositories and transform them into profitable services that aid in decision-making for various stakeholders. Recent research topics address precise data collection and engineering to serve knowledge creation of new farming models, technology application in farming, resource allocation, assessment frameworks for risk, policy definition and quality management. Additionally, researchers are focusing on qualifying decision models and identifying decision parameters such as region, land, climate, plant, time, and process (Lezochea et al., 2020).

2.8. Automation and robotization

Digital technologies have enabled machines and robots to perform tasks that were previously done by humans. Automation and robotization are driving the development of smart agriculture and accelerating the transition to smart factories in the food industry (Hassoun et al., 2022). In agri-food processing, robotics can automate tasks such as seeding, planting, weeding, picking, handling, harvesting, cutting, slicing, and packaging, thereby improving efficiency and reducing labor costs (Botta et al., 2022). Fig. 2 provides a summary of the sectors in which technologies are used in the food industry.

3. Recent advances in digital technologies for food safety and quality control

It is estimated that approximately 600 million people fall ill after eating contaminated food, and 420,000 die every year. Therefore, it is necessary to adopt a risk-based approach to food production. This is the main reason why the Codex Alimentarius Commission (2016) has adopted certain risk management measures, with specific tools and concepts such as food safety objectives (FSOs) and performance objectives (POs). This has also accelerated the need to build a more sustainable food system using innovative solutions for food resilience while taking into account economic and environmental constraints (Guruswamy et al., 2022).

Industry 4.0 is a way to guarantee food demand and food security sustainability, as it integrates information and communication technologies such as IoT, industrial IoT (IIoT), cobots, cloud computing, big data analytics, artificial intelligence (AI), digital twin (DT), blockchain,

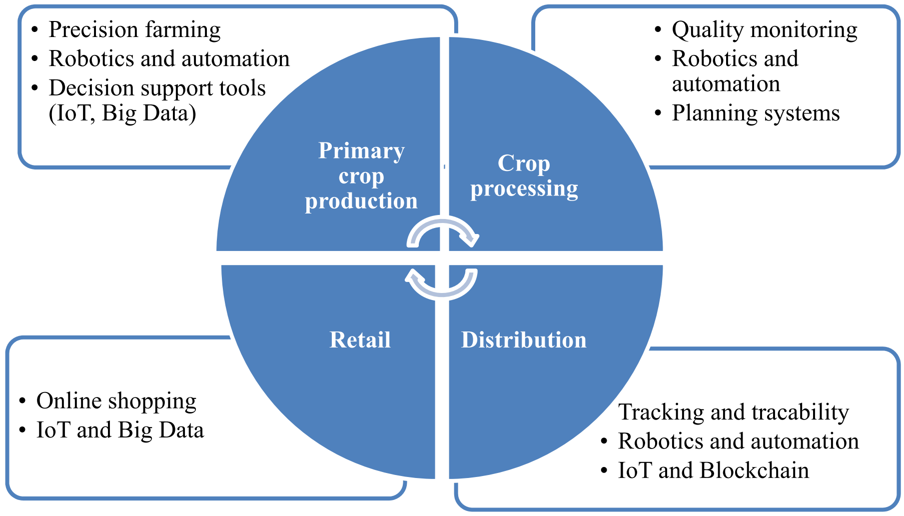

Fig. 2. Concept of digitalization in the agri-food supply chain.

sixth-generation (6 G) communication technology and machine learning (ML) (Flamini & Naldi, 2022; Guruswamy et al., 2022). These technologies can be used digitally for various purposes, including data collection, transmission, processing (such as visualizing the factors impacting food quality and analyzing food waste), management, and analysis. Their implementation aims to tackle challenges and optimize supply-chain activities, thereby enhancing food security and integrity throughout the entire journey from farm to consumer. Furthermore, these technologies contribute to cost reduction and waste minimization efforts. Other tools, such as traceability software and radio frequency identification, have the potential to improve the food traceability system (Ingram & Maye, 2020; Raja et al., 2022; Guruswamy et al., 2022).

By prioritizing food safety and quality control and harnessing the potential of advanced technologies, we can significantly mitigate the risks associated with contaminated food and create a more secure and sustainable food system. The integration of risk-based approaches, innovative solutions, and traceability measures will serve as the pillars of a robust framework that safeguards public health and ensures the provision of safe and high-quality food to consumers.

4. Digital technologies for improving efficiency and sustainability in agri-food processing

Agriculture and food processing face many challenges, including the need to improve efficiency and sustainability to meet the increasing demand for food while minimizing environmental impacts (Nicolétis et al., 2019; Bahn et al., 2021). Digital technologies have the potential to transform agri-food processing by improving productivity, reducing waste, and optimizing resource use (Scuderi et al., 2022).

Recent studies have shown that digital technologies, such as sensors, drones, and GPS systems, can assist farmers monitor crop health, optimizing irrigation and fertilizer use, and reducing waste. Through the implementation of precision agriculture techniques, farmers have the ability to increase food production while minimizing resource usage, ultimately leading to a reduction in the environmental impact of agriculture (Zhao, Wang, & Pham, 2023). Predictive analytics, which leverage machine learning algorithms to analyze large datasets and predict potential problems before they occur, can optimize processing and production, reduce waste, and improve food safety and quality (Belaud et al., 2019; Oltra-Mestre et al., 2021).

Additionally, digital technologies, such as blockchain and RFID, can track product movement through the supply chain, enabling companies to optimize logistics, reduce waste, and improve traceability and transparency (Attaran, 2020; Varriale et al., 2021; Chandan et al., 2023). Automation technologies, such as robotics and AI, can improve efficiency and reduce labor costs in agri-food processing. For instance, robots can harvest crops, reducing the need for manual labor and increasing productivity (Mor et al., 2022; Lezoche et al., 2020).

Finally, digital technologies can optimize energy use in agri-food processing facilities. For example, smart lighting and heating systems can automatically adjust energy use based on occupancy and weather conditions, reducing energy waste and costs (Abbate et al., 2023; Lai et al., 2020). Fig. 3 showcases the various stages of agri-food processing and the digital technologies that can be used to improve efficiency and sustainability in each stage, while Table 1 highlights recent results in digital technologies for improving efficiency and sustainability.

5. Case studies of digital technology applications in agri-food processing

Recent studies have reported technologies that have been successful in the food industry (Saurabh & Dey, 2021; Feng et al., 2020; Gu et al., 2021). For instance, IBM Food Trust, Blue River Technology, OAL Connected, The Yield and many more (refer to Table 2).

5.1. IBM food trust

IBM Food Trust is a blockchain-based platform that enables transparency and traceability in the food supply chain. The platform has been used to track the journey of mangoes from farm to store shelves. The platform enabled quick identification of the source of a food safety issue, resulting in the recall of affected products and preventing further contamination (Khan et al., 2022). IBM Food Trust has been the subject of numerous scientific articles reporting on its efficacy and potential to revolutionize the food supply chain. The platform utilizes blockchain technology to ensure transparency and traceability from farm to store shelves (Singh et al., 2021). Studies have shown that this tool has been effective in improving food safety by enabling the quick identification of the source of contamination (Rejeb et al., 2020). Moreover, the IBM Food Trust has been proven to be beneficial for sustainability and reducing waste in the supply chain (Howson, 2020). By providing a digital platform for tracking products, it allows for more efficient inventory management and reduces food loss due to spoilage or expiration (Howson, 2020). In addition to its practical applications, researchers have also explored the potential of the IBM Food Trust for creating new business models and enhancing trust between different stakeholders in the food industry (Lacity & Van Hoek, 2021).

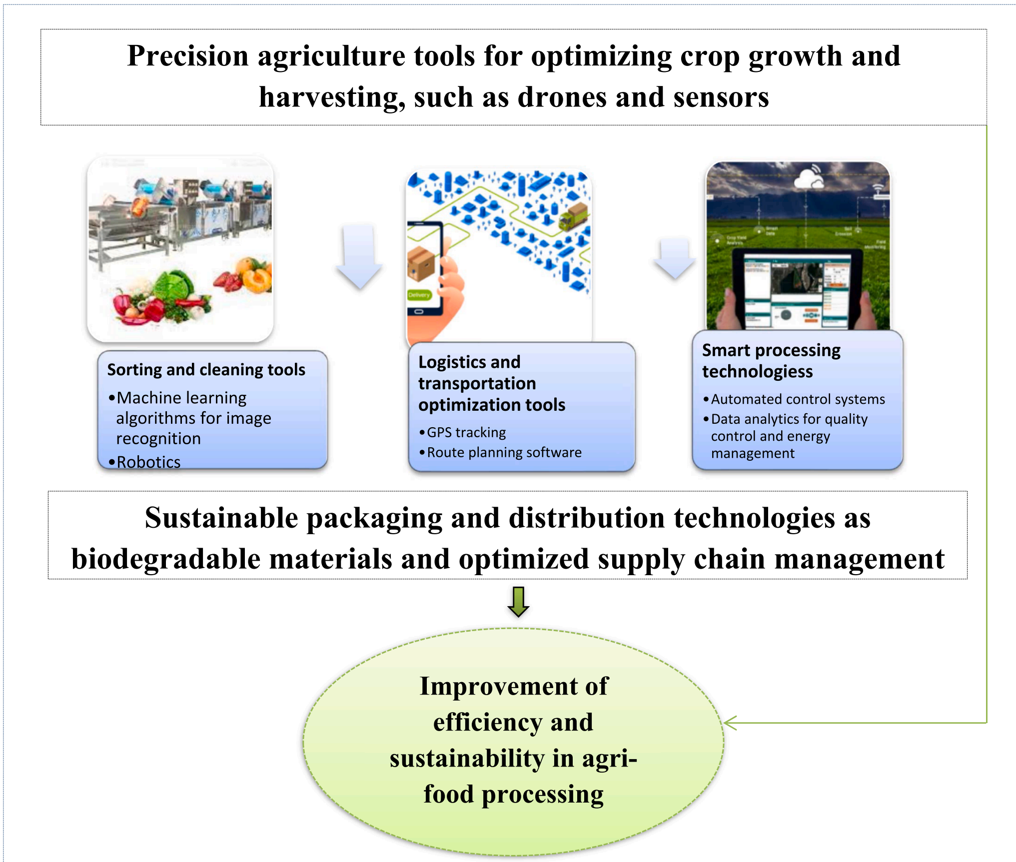

Fig. 3. Flowchart presenting various stages of agri-food processing and the digital technologies that can be used to optimize each stage for improving efficiency and sustainability.

5.2. Blue river technology

Blue River Technology has developed a weed-removal machine that uses computer vision and machine learning to identify and remove weeds from crops. The technology identifies individual plants and selectively applies herbicides, reducing the amount of chemicals required and potentially increasing crop yields (Fennimore & Cutulle, 2019).

Research has demonstrated that effectiveness of this technology in reducing herbicide use, with one study reporting a 90% reduction in herbicide application in cotton fields (Malkani et al., 2019; Toscano-Miranda et al., 2022). The See & Spray technology also has the potential to reduce labor costs and improve efficiency in crop management (Abbas et al., 2020).

Blue River technology's autonomous technology has also been applied to other crop management tasks, such as crop thinning and planting, showing promise in reducing the time and labor required for these tasks (Fennimore & Cutulle, 2019). Moreover, this technology has the potential to reduce environmental impacts by targeting weeds specifically and avoiding unnecessary herbicide application, which can contaminate soil and water systems (Fennimore & Cutulle, 2019).

5.3. The yield

The Yield is an agricultural technology company that specializes in providing digital solutions to improve crop management and decision-making in the agriculture industry. One of their primary offerings is a digital platform that uses sensors, weather data, and machine learning algorithms to optimize irrigation scheduling, resulting in increased yields and improved resource efficiency (Sharma et al., 2020). The platform has been successfully implemented in various agricultural contexts, including the production of almonds, grapes, and cotton, and has shown significant improvements in crop yield and water use efficiency.

In addition to optimizing irrigation scheduling, The Yield's platform also provides real-time monitoring of weather conditions and soil moisture levels. This enables farmers to make data-driven decisions about crop management, pest control, and harvesting (Ramachandran et al., 2022). One of the key benefits of The Yield's technology is its ability to provide customized recommendations for individual farms based on their specific conditions and needs. This level of customization has the potential to significantly improve the efficiency and profitability of agricultural operations, while also reducing environmental impacts. However, the adoption of The Yield's technology also raises concerns related to data privacy and security, as well as potential job displacement in the agriculture industry (Tsouros et al., 2019). These issues will need to be addressed to ensure implementation of this technology.

Studies of digital technologies in agri-food processing have demonstrated numerous benefits, including improved efficiency, increased productivity, enhanced food safety and quality, and reduced environmental impact. Nonetheless, it is imperative to take into account certain constraints. One of the main limitations is the cost of implementing digital technologies, which can be a significant barrier for small and medium-sized enterprises. Additionally, the complexity of some digital technologies and the need for specialized skills and knowledge to operate them can also be a challenge for some producers. Moreover, the use of digital technologies can raise concerns about data privacy and security. Therefore, it is important to carefully evaluate the benefits and limitations of digital technologies before their adoption in agri-food processing (Table 2).

Table 1
Summary of recent results in digital technologies for improving efficiency and sustainability.

Studied aspects	Experimental setup	Major findings	References
The Middle East and North Africa (MENA) region's potential, status, and risks related to the adoption of digitalization for sustainable agri-food systems.	Review of both scholarly and non-scholarly resources, such as materials from the World Bank and FAO.	Digital agriculture has great potential to solve issues in the MENA agri-food sector through better production, supply chain optimization, and the use of natural resources.	Bahn et al., 2021
Implementation, obstacles, and potential future research paths of utilizing blockchain technology for managing the agri-food value chain.	Systematic literature review and citation network analysis.	A blockchain-based experimental device was used to improve agri-food value chain management in aspects such as traceability, information security, manufacturing, and water management.	Zhao et al., 2019
Utilizing big data in agri-food 4.0 for managing the supply chain of by-products sustainably.	Evaluation of different processes and their technological panels by analyzing their environmental impacts on the project.	A novel strategy has been formulated to incorporate large-scale data analytics to improve supply chain sustainability.	Belaud et al., 2019
Examining the supply chains and technologies anticipated for the future of agriculture.	A survey was conducted on supply chains and technologies in agri-food 4.0.	Agri-food 4.0 requires IoT, blockchain, and AI technologies for sustainable and efficient supply chains.	Lezoche et al., 2020
Leveraging Industry 4.0 possibilities to drive innovation in the Agri-Food industry.	Review paper analyzing the opportunities for Industry 4.0 in the agri-food sector.	The agri-food sector can benefit from Industry 4.0 technologies such as precision agriculture, blockchain, and smart packaging. Successful implementation requires a focus on collaboration and a willingness to adapt.	Oltra-Mestre et al., 2021
The potential off utilization of blockchain technology in the agri-food sector	Conducted pre-literature review, formulated research questions, identified case studies, and analyzed to answer questions.	Blockchain is used in the agri-food chain for trust and transparency, but governance issues arise for sustainable applications.	Motta et al., 2020
Implementation and design of blockchain technology in the creation of sustainable agrifood supply chains.	Rating-based conjoint analysis was used to identify potential drivers of blockchain adoption in the grape wine supply chain.	The study identifies key factors (compliance, dis-intermediation, price, trust, traceability and coordination) affecting supply chain adoption decisions and emphasizes the need for a modular and sustainable supply chain architecture.	Saurabh and Dey, 2021
Exploring opportunities for lean and green manufacturing through water telemetry in the agri-food industry to promote sustainability.	Use of water telemetry to identify lean-green improvement opportunities in agri-food industry.	Water telemetry identified opportunities for improvement in water consumption and wastewater treatment, leading to potential savings and environmental benefits.	Viles et al., 2021
Analyzing the interaction between the agri-food industry and artificial intelligence.	The review article analyzes the relationship between AI and agri-food industry.	AI can revolutionize agri-food, including improving crop yields, reducing waste, and optimizing supply chain management but needs ethical management	Rejeb et al., 2022
Examining the influence of digital technologies on accomplishing the Sustainable development goals in the agri-food industry through empirical evidence.	A cross-case analysis of Italian agri-food companies' sustainability reports identifies digital technologies used and their association with SDGs.	Digital technologies have a positive impact on the achievement of Sustainable Development Goals in the agri-food sector.	Secundo et al., 2022
Innovation and Challenges in the Application of Robotics and Automation to Agri-Food 4.0."	Review article	The review discusses the challenges and innovations related to using robotics and automation in Agri-Food 4.0.	Mor et al., 2022
The Role of Internet of Nonthermal Food Processing Technologies (IoNTP) in Food Industry 4.0 and Sustainable Practices	Review and conceptual study analyzing existing literature and case studies.	Overview of digitalization, IoT, 3D printing, cloud data storage, and smart sensors in Nonthermal Food Processing Technologies (IoNTPs) and sustainability. Identifying the potential benefits of energy savings, improved environmental performance, cost optimization, and alignment with sustainable development goals (SDGs) and Agenda 2030.	Režek Jambrak et al., 2021
Investigation on the adoption of digital technologies (DT) in agri-food supply chains to address food security concerns in developing countries during the COVID-19 pandemic	Review and conceptual study analyzing existing literature and case studies.	The research emphasizes "Digital Technologies, Logistics, and Infrastructure" as the crucial factor for managing food security in developing economies during COVID-19.	Joshi and Sharma, 2022

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Table 1 (*continued*)

Studied aspects	Experimental setup	Major findings	References
		It enables data-driven decision-making and survival in disruptive environments, benefiting farmers and supply chain partners in ensuring a smooth flow of food items and enhancing agri-food supply chain resilience through digital transformation.	

6. Future directions for digital technologies in agri-food processing

The use of digital technologies in agri-food processing is becoming increasingly important as the industry faces the challenges of increasing demand, resource constraints, and sustainability concerns. The adoption of digital technologies can help to improve efficiency, productivity, and sustainability while also improving food safety and quality (Bahn et al., 2021). For example, IoT sensors are becoming more affordable and accessible, and they can be used to collect real-time data on soil conditions, crop growth, and environmental factors (Muangprathub et al., 2019). As the use of IoT sensors becomes more widespread, farmers and food processors will be able to make more informed decisions about planting, harvesting, and processing, resulting in increased efficiency and reduced waste (Alladi et al., 2020). Also, AI and machine learning can help farmers and food processors make more accurate predictions about crop yields, optimize processing parameters, and detect food safety issues more quickly (Kler et al., 2022). As these technologies become more sophisticated, they will be able to identify patterns and trends that are not visible to the human eye, resulting in improved efficiency and productivity (Baduge et al., 2022). Moreover, blockchain technology can help improve transparency and traceability in the food supply chain, which is becoming increasingly important to consumers. As the cost of implementing blockchain technology decreases, it is likely that more companies will adopt this technology to enhance their supply chain management (Madumidha et al., 2019; Centobelli et al., 2022). In addition, the development of new robotics technologies can help reduce the need for manual labor in agriculture and food processing, resulting in increased efficiency and reduced costs. As robotics technology becomes more advanced and affordable, we will see more automation in the agri-food industry (Marinoudi et al., 2019). Furthermore, 3D printing has the potential to revolutionize the way that food is produced, allowing for highly customized products and reducing waste (Pereira et al., 2021; Baiano, 2022). This technology is still in its early stages, but there is potential for it to become more widespread in the future. Finally, virtual and augmented reality technologies could be used to simulate agricultural processes and help farmers and food processors identify areas for improvement. This technology could also be used for training purposes, allowing workers to gain experience in a safe and controlled environment (Ronaghi et al., 2021). To achieve these benefits, it will be necessary to overcome the challenges associated with cost, access to technology, technical expertise, and resistance to change (Abioye et al., 2021; Vern et al., 2022). Overall, the potential for future developments in digital technologies for agri-food processing is vast, and there are many exciting areas where progress could be made. As these technologies continue to advance, they will likely play an increasingly important role in ensuring the sustainability and efficiency of the agri-food

Table 2
Analysis of benefits and limitations of digital technologies in agri-food processing case studies.

Technologies	Benefits	Limitations	References
IBM Food Trust	- Improves the efficiency of the food supply chain through internet connectivity and smart sensors. - Reduces product waste, inventory costs, and time variance - Enables the industry to enhance product production, food safety, and agricultural practices over time. - Provides transparency in food product processing empowers consumers by providing awareness of quality, safety, and environmental impact, meeting their demands for assurance. - Reduces costs for the public health system, improves accessibility for auditing authorities, and enhances government oversight.	- The integrated system for food product traceability is still in its early stages, and discussions about future infrastructure responsibility are ongoing. - The impact of the distribution algorithm on small and medium enterprises, self-owned farms, and developing countries is a controversial issue that requires attention. - Small businesses may find it too expensive.	Chen and Long, 2021 Opinion of the authors
Blue River Technology	- Reduces herbicide use, costs, and environmental impact. - Improve agricultural performance. - Enabling easier customer feedback collection - Making informed decisions based on crop issues - Creating automated machinery for precision farming - Utilizing machine learning and computer vision in agriculture to address on-field challenges - Assisting farmers by teaching machines how to farm effectively	- Small farmers may find purchasing and implementing Blue River Technology expensive. - The machine may not accurately identify all weeds.	Panpatte and Ganeshkumar, 2021 Opinion of the authors
The Yield	- Assisting in optimizing farm input utilization for minimal environmental impact - Identifying ideal timeframes for irrigation, nutrition, and safe sprays to meet crop requirements efficiently	- Implementing may be expensive for small farmers. - The system may require technical expertise to operate.	Sharma et al., 2020 Opinion of the authors

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Table 2 (*continued*)

Technologies	Benefits	Limitations	References
	- Particularly beneficial for weather-sensitive biologicals, promoting environmental safety - Ensuring crops receive necessary inputs precisely when most beneficial - Contributing to sustainable agriculture practices by reducing environmental impact		
Taranis	- Uses drones, satellites, and sensors to monitor crops and fields in real-time. - AI and machine learning algorithms analyze data to provide actionable insights for farmers, improving efficiency, reducing waste, and increasing profitability.	- Implementing may be expensive and require specialized expertise to operate. - May be limited in effectiveness under certain weather conditions or with certain crop types.	Bacco et al., 2019 Opinion of the authors
HarvestMark	- Can improve transparency, trust, and safety in the food supply chain by helping food producers and retailers track their products from farm to fork using QR codes and other technologies. - May require significant changes to existing production and supply chain processes, and may not be effective if consumers are not willing to engage with the tracking system.	- Could need significant supply chain changes and might not work well if not widely accepted. - Sensitive information collected and stored could raise data privacy and security concerns.	Lukens, 2015
Esoko	- Provides farmers with real-time information on market prices, - Enables farmers to make informed decisions regarding marketing and selling their produce. - Facilitates access to weather information and alerts, helping farmers plan their farming activities. - Supports the integration of farmers into agricultural value chains and markets. - Subscribing to Esoko also allows users to be aware of buying and selling offers posted on the SIM website by other subscribers.	- Relies on reliable data sources and regular updates to provide accurate and up-to-date information. - May require training and support to ensure effective utilization by farmers and other users. - The fact that the Esoko SIM disseminates information provided by users without conducting an investigation can potentially lead to a risk of information manipulation	Van Schalkwyk et al., 2017 Agnissan et al., 2022

industry.

7. Conclusion

In conclusion, digital technologies present a transformative opportunity for the agri-food industry, offering significant advantages in efficiency, food safety, sustainability, and transparency. The increasing integration of IoT, AI, blockchain, and robotics in agri-food processing showcases successful implementations and foreshadows a promising future. However, to realize the full potential of these technologies, addressing key challenges is imperative. Cost, technological accessibility, technical expertise, and resistance to change pose critical barriers that demand concerted efforts from all stakeholders in the agri-food sector. In perspective, targeted advancements in specific digital technology domains, such as big data and analytics, autonomous systems, 3D printing, virtual and augmented reality, and blockchain, hold immense promise for the industry. Through continuous innovation and collaboration, the agri-food sector has the opportunity to cultivate sustainability, efficiency, and transparency for the benefit of farmers, food processors, and consumers.

Ethical statement–Studies in humans and animals

This study was conducted without utilizing any human or animal resources.

Declaration of Competing Interest

There are no conflicts of interest in connection with this paper, and the material described is not under publication or consideration for publication elsewhere.

Data availability

Data will be made available on request.

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