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Digital innovations in the post-pandemic era towards safer and sustainable food operations: A mini-review

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Though the pandemic has created an imbalance and disrupted the economy in the food industry, it has had a positive impact on speeding the acceptance of the industry towards digital innovations (DI). The shift toward digitalization is leading the food industry to leverage innovations that can serve the dual purpose of safer and sustainable food operations. This review synthesizes the rapidly growing literature on digital technology used as the response to the emergence of food safety and sustainability issues during the COVID-19 pandemic. Opportunities to improve thirteen food safety management system components and three sustainability components including economics, environmental and social were identified. The review determined that blockchain and IoT have the most prominent role in improving food safety, especially the component of traceability and monitoring and inspection.

KEYWORDS

digital innovations, post-pandemic, food safety, sustainability, COVID-19 effects, blockhain, IoT, Technology management

1 Introduction

The COVID-19 pandemic caused greater depression in terms of economic loss, affected all economies and society, and paralyzed the world (Linton and Vakil, 2020; Paul and Chowdhury, 2020). In the immediate term, the pandemic affected the industry due to the complex network of food production, supply, and consumption by causing labour problems (e.g., lack of workers due to illness and quarantine measures), factory shutdowns, food scarcity on shelves, and liquidity stress for active businesses

An efficient food supply chain (FSC) means sustainable, sufficient, affordable, and safe food able to be provided to the end-user (Kazancoglu et al., 2022; Lee et al., 2021). The pressure is being created by different stakeholders associated with FSC during the pandemic Covid 19 due to free trade strategies, disruptions, food defense, food fraud, and globalization, besides the safe, hygienic, and quality foods (Zhang et al., 2021). It is an area of prominence, making it critical to successfully apply advanced technologies to ensure an efficient food supply chain (FSC). The available information is limited to specific digital technologies, but there is no previous study publication that summarised the potential digital technologies for food safety and sustainability for the FSC stakeholders.

Through a long reflective lens, lessons have been learned from previous catastrophic global events, such as the Spanish Flu or Black Death, where inspiration has led to paradigm shifts in disruptive technologies that change the practices in the post-pandemic. The post-pandemic era is considered the era after the government relaxed the lockdown imposed on the people and businesses.

Food safety and sustainability are recognized as strongly affected dimensions of food systems due to the practices during the COVID-19 pandemic (Galanakis, 2020). On a long-term basis, the pandemic affects the whole food sector in the domain of food safety, bioactive food ingredients, food security, and sustainability (Galanakis, 2020; Djekic et al., 2021; Qian et al., 2022). Innovative solutions are needed as supply chains are mostly inefficient, with increasing constraints and demand. On the verge of a significant global recession and disruptions of FSC during the COVID-19 pandemic, it is lacking critical information for recovery and other mitigations of the challenges to face post-pandemic era (Guan et al., 2020). Therefore, to fill the current gap in the literature and concur with suggestions by Khan et al. (2021) and Zhang et al. (2021) this study is focusing on mapping the emergence of digital innovations (DI) due to the COVID-19 pandemic and assessing the opportunities of the DI in the food safety and sustainability for transitioning beyond COVID-19 pandemic era. The post-COVID-19 pandemic era witnessed producers, manufacturers, retailers, governments, and policymakers all strongly interconnected in identifying emerging technology to making decisions, identifying and implementing key solutions, as well as in solving critical challenges in the FSC (Quayson et al., 2020; Lee et al., 2021). This paper presents a thematic narrative review aimed at answering the following research questions:

a) What are the issues in the post-Covid 19 pandemic era in terms of food safety and sustainability?
b) What are the opportunities for digital technologies application toward safer food?
c) What are the opportunities of digital technologies to create a sustainable FSC?

2 Research approach and design

Narrative review articles are publications that are comprehensive, critical, and objective analyses of the current state of a topic from a theoretical and contextual point of view. The literature searches were carried out using Scopus, Web of Science, Google Scholar, and ProQuest. Scholars have recommended the exclusion of conference proceedings to ensure the data extracted are based on quality sources. The keywords and search strings used in this study were Digitalisation and Food, Post-pandemic and Food, Food and Industry 4.0, Digital and Post-pandemic and Food, Smart Food Safety, Digital and Sustainable Food Supply Chain, Blockchain, and Food.

2.1 Selection process

The selection procedure was broadened by using the references of the selected publications and publications using English are considered. Quantitative studies were considered if the main research addresses the digitalized food supply chain. Two researchers evaluated the research's validity and reliability by identifying methodological limitations and biases. Qualitative or conceptual studies that focused on broader questions were included. Very few articles focused on FSC4.0; however, articles dealing with digital technologies in the FSC processes were analysed to obtain its opportunities for improving food safety and sustainability performance.

2.2 Narrative literature review process steps

This study employed (Sony et al., 2020) qualitative–interpretive approach like grounded theory for data analysis. The review commenced by reading the identified selected articles to familiarise themselves with the contents, followed by introspection reflection. Then, open coding by associating significant words or phrases to data so that it can be distinguished from the entire data. The thematic categories produced in open coding phases were then assessed to infer linkages between the topics. This allows for second-order classification toward primary themes. To ensure the reliability of the results, the authors analysed the data and debated it until a consensus was reached.

3 Impact of the COVID-19 pandemic on food safety and sustainability

The COVID-19 pandemic is considered a black swan event because it highlighted unforeseeable disturbances that might have disastrous effects on the whole food supply system. Several reports discuss the effect of the pandemic on the food industry from the perspective of food supply and demand, and it has a ripple effect from supply-demand issues to food safety and sustainability. This assessment identifies that the disruption related to food safety and sustainability extends throughout the supply chain's production, supply, logistics, demand, and personnel.

3.1 COVID-19 post-pandemic era related to food safety

Although there is scant evidence that SARS-CoV-2 may be transferred through food, this does not rule out the possibility that SARS-CoV-2 will be transmitted during the food chain. SARS-CoV-2 is risking food safety through the touch of the infected food handler with poor hygiene practices and the water used in the processing such as fresh salads or shellfish grow (Yu et al., 2022).

3.1.1 Food safety risk of infection

In the previous outbreak of MERS and SARS-CoV viruses, food was considered less likely to be a route of transmission (Galanakis, 2020; Rzezutka et al., 2020). Although the coronavirus is mainly transmitted through droplets and close contact among humans, the possibility of transmission through water, bioaerosols, and food should not be ignored (Ceylan et al., 2020). However, there is very little evidence showing the potential risk of infecting COVID-19 from contaminated food or packages of food (Rzezutka et al., 2020). Therefore, based on the literature, it can be concluded that SARS-C0V2 is not considered a foodborne virus, but the processes along the food supply chain are considered a high risk of virus transmission.

As a result of the COVID-19 pandemic, response plans for food workers were designed to guide operations in food processing facilities and manage coronavirus in the food industry (Galanakis et al., 2021). COVID-19 crisis causes response plans for food workers were developed to provide guidance for the continuity of operations in the food processing facilities and manage coronavirus in the food industry. Especially meat and poultry processing industries can be defined as the critical infrastructure in food and agriculture. The plan includes a hierarchy of control requirements for cleaning, sanitation, disinfection of facilities, screening, and monitoring of workers for COVID-19, managing sick employees, and education programs for workers and supervisors to prevent the spread of coronavirus (FDA, 2020).

Several current food safety management system (FSMS) standards embodied the requirements associated with emergencies such as BRC, FSC2200, ISO 22000, and IFS except for HACCP which does not specifically outline the need for the companies to manage their emergencies. However, there are missing definitions of the type of emergencies the food companies may have to address. Plans for dealing with emergencies typically include implementing preventative measures where applicable, guidelines on how to handle possible emergencies and accidents, a reporting protocol, and root cause analysis, with plan revisions if necessary. For post-Covid 19 situations, there is an urgency to include the plans in case of water, packaging, and ingredient contamination (Djekic et al., 2021).

3.2 How pandemic change the sustainability of the FSC?

The COVID-19 pandemic caused an imbalance at a sustainable level (economic, social, and environmental) of global supply chains (Kazancoglu et al., 2022). Out of 1,000 top companies, more than 94% have been affected by the COVID-19 pandemic (El Baz and Ruel, 2020). Sustainability in FSC means providing process continuity with minimal losses, and it is a continuous challenge (Yadav et al., 2020). This uncertain time endangers the sustainable FSC (Quayson et al., 2020; Lee et al., 2021), where farmers have trouble accessing the sources that comprise the first stage of the FSC and affect manufacturing capacity, and logistical issues occur in the FSC, such as difficulty accessing raw materials (Pereira et al., 2021), loss of cooperation between suppliers, and communication problems in the processes (Barman et al., 2021). FSC management aims to protect food safety and quality and is the coordination of business processes to ensure the sustainability of product and information flow throughout the chain (Anastasiadis et al., 2018). Critical lessons change the dynamic of the food industry when logistics networking has become vital for firms since they need to manage their activities effectively to deal with disruptions in the supply chain. Managerial approaches are forced to adopt approaches that will provide flexibility to adapt to constantly changing conditions (Jones et al., 2021). However, the pandemic lockdown has a positive effect, the closures of industrial and business activities result in the restoration of the ecological system and reduce carbon emission levels (Joshi & Sharma, 2022).

3.3 Role of digital technologies in the post-pandemic era

The lessons learned from the COVID-19 pandemic from the lens of food safety, it is imperative to create new capabilities and approaches to deal with the uncertainty in new normal environments. Post-pandemic period brings in technological solutions, virtual office working, digital payment culture, remote audits, and online performance monitoring systems transforming industrial practitioners into an on-demand model with permanent internet access (Accorsi et al., 2017; Jones et al., 2021). According to Deloitte, the COVID-19 pandemic has accelerated 77 percent of CEOs' digitalisation plans and faster and broader adoption of data (Kane et al., 2020).

Digital solutions emerged as the most often discussed long-term strategy for protecting the supply chain from large-scale pandemic-caused disruptions (Quayson et al., 2020; Abdul et al., 2021). Digital solutions promise to provide flexibility, connectivity, visibility, and agility, all of which are resilience capabilities that can better prepare supply chains to manage future disruptions (Queiroz and Wamba, 2019; Kittipanya-ngam and Tan, 2020; Nasiri et al., 2020; Quayson et al., 2020; Hald and Coslugeanu, 2022).

When the COVID-19 globally affect the world, a national lockdown was implemented, which disrupted FSC due to closed borders, and a shortage of food. The slowing of the food business economy has caused a surge in e-commerce and digital transformation. Foodservice provision has experienced new opportunities with digital services, providing free contactless meal ordering and interactive maps for citizens to find free meals during the pandemic (Lee et al., 2021). Isolated households could order and receive household items from the autonomous delivery robot. E-commerce adoption by big and small vendors and restaurant enterprises ensured consumer food access (Abdul et al., 2021).

3.3.1 DI for a safer food system

Innovations such as smart and active packaging, advanced smart traceability systems, new biosecurity arrangements (e.g., promoting a food safety culture in food processing facilities and farms), the application of biopesticides to agriculture and industry 4.0 (e.g., blockchain, IoT, technology) are expected to grow substantially in the new era (Galanakis et al., 2021; Yu et al., 2022). These innovations may lead to new business models that could disrupt the FSC and the market of food products in a techno-socioeconomic way. The food and Drug Administration (FDA) is planning to release a relevant blueprint targeting the development of traceable food systems and secure food supply (FDA, 2020). Technologies such as artificial intelligence, blockchain, the Internet of Things (IoT), and sensor technology would allow the direct tracking of foods and commodities from farm to fork (Maragoni-Santos et al., 2021; Rahman et al., 2021). The combination of advanced traceability systems with modern analytical and smart tools (e.g., remote inspections, and root cause analysis) would reduce the response to foodborne outbreaks by using data streams (Kittipanya-Ngam and Tan, 2020; Yu et al., 2022). The latest could make the supply chain more visible, reducing the time between tracking the contamination origin of food and responding with mitigating actions. These kinds of technologies would also assist in imbalances caused by panic buying and spot shortages due to extreme events and help comprehend the causes of food contamination and interpret predictive analytics (Abdul et al., 2021; Hald and Coslugeanu, 2022).

A major goal for containment in the pandemic era is reducing the time delays in the identification of diseases at their source. Real-time health data, collected through smartphones and watches, can be leveraged to identify emerging food outbreaks in both humans and animals (Yu et al., 2022). Utilizing internet search histories based on the frequency of health queries in disease hotspots can be utilized as well (Talari et al., 2022). Data analytics software can incorporate past information on zoonotic diseases and socioeconomic information on livestock production and consumption patterns (Lee et al., 2021). Local food labs that test food quality should be equipped with surveillance technology and given access to data repositories to identify threats coming from food value chains (Jarzębowski et al., 2020). Health researchers, food safety practitioners, epidemiologists, and regional food partners must collaborate to improve surveillance.

Embracing and accepting IR4.0 in FSMS can be a challenge due to the resistance, which is why it is imperative to clearly understand the opportunities DI brings to each component of FSMS as shown in Table 1. Digitalization in FSMS could accelerate the progress of FSMS, which continuously faces numerous obstacles in terms of designing, implementing, and validating the food safety system. Table 1 reviews the opportunities for digital technologies to integrate with FSMS.

DI shown in Table 1 are the common tools applied for the development of a viable FSMS which comprises 13 components. DI identified as critical for food safety purposes are blockchain, and IoT (RFID), especially in terms of monitoring and traceability. Traceability is defined by Codec Alimentarius Commission (CAC), as the ability to follow the movement of food through a specified stage of production, processing, and distribution (CAC/GL60, 2006). The ideal smart food traceability system can track the location of any food, the ingredients it contains, and its packaging at any location in the supply chain where it has a critical role in food recall. The critical challenge to establishing a practical smart traceability system is that a product may contain multiple ingredients which may come from different sources locally or a massive amount of traceability data that is still unable to be analysed (Yu et al., 2020; Zhang et al., 2021). According to the literature, blockchain and is the most mature DI application for food safety purposes. Although blockchain was initially used to record financial transactions, its application has evolved for food safety purposes, specifically to ensure that data in the food production process will enable the timely disclosure of knowledge such as source, batch number, and manufacturing date, and also the accountability and honesty of the manufacturing process (Rahman et al., 2021), food safety certification (Zhang et al., 2021), and organic products, which help in promoting food safety (Yadav et al., 2020).

Compared to the blockchain, IoT application for food safety purposes is still in an early stage and further innovations are still needed to capture the full potential of IoT to offer. Studies suggested, to facilitate real-time monitoring and control, IoT

TABLE 1 Opportunities of digital technologies for a safer food.

Component of FSMS	Technology/Level of utilisation	Opportunities	Country	Ref
Traceability	Blockchain (High utilisation)	Blockchain can create creates a decentralized, immutable food safety record of all transactions and every step from production through delivery	China	Tao et al. (2019)
				Feng et al. (2020)
				Tian (2017)
				Hao et al. (2021)
				Tian (2017)
				Zhang et al. (2020)
				Zhou et al. (2022)
			Spain	Galvez et al. (2018)
			Hong Kong	Tse et al. (2018)
			UAE	Kshetri (2019)
			United States	Salah et al. (2019)
			Thailand	Surasak et al. (2019)
			Austria	Casino et al. (2019)
			Greece	Lin et al. (2019)
				Surasak et al. (2019)
				Casino et al. (2019)
	IoT (Medium utilisation)	IoT technologies such as Wireless Sensor Networks (WSN) and Radio Frequency Identification (RFID), NFC, and QR Code track and record food products for food safety traceability schemes	China	Liu et al. (2018)
			Europe	Brewster et al. (2017)
	Artificial intelligence (Minimal utilisation)	Visualization approach to illustrate hazards and improve food traceability assessment	China	Hao et al. (2021)
Data and documentation	Blockchain (Low utilisation)	Blockchain keeps a permanent record of each transaction, separated into blocks that cannot be altered	Hong Kong	Tse et al. (2018)
			Spain	Sgroi (2022)
	IoT (Medium utilisation)	Able to ensure online data collection in the chain	Canada	Astil et al. (2019)
Product Information	Blockchain (Low utilisation)	Fast-tracking of meat products using QR Code	United States	Kshetri (2019), Dadi et al. (2021),
	Cloud Computing (Low utilisation)	Enable storage of product-specific information	Greece	Nychas et al. (2016)
Product Recall	Blockchain	Blockchain effectively handles food contamination in a food retail crisis	United States	Kshetri (2019)
Risk assessment	Big Data (Low utilisation)	Bayesian Networks predict the food safety risk through climate change, economy, and human behavior	Ireland	Talari et al. (2022)
	Blockchain (Low utilisation)	Creating a stable database of knowledge flows-decreases food safety risks-raises customer interest	Italy	Longo (2019)
Monitoring and inspection	Blockchain (Low utilisation)	Inspection of food quality and safety available for consumers	China	Zhou et al. (2019)
		Blockchain allows more determined identification and removal of contamination sources	German	Creydt and Fischer (2019)
		Allowing a better foreign trade supply chain based on safe trade	UAE	Juma (2019)
		Preventing counterfeit products and tracking the transportation environment		
	IoT (High utilisation)		Netherlands	

(Continued on following page)

TABLE 1 (*Continued*) Opportunities of digital technologies for a safer food.

Component of FSMS	Technology/Level of utilisation	Opportunities	Country	Ref
		IoT enables remote monitoring of shipping positions and conditions		Verdouw et al. (2018)
		Improving food safety monitoring using online sensor-based monitoring	United Kingdom	Rahman et al. (2021)
		Smartphones can be used as fluorescence detectors and detection information receivers to determine the levels of the chemical in food	France	Bueno et al. (2016)
		Monitoring of food supply chains where the cloud is used to store physical object-related data	France	Mededjel et al. (2017)
		Food monitoring, and biological sensing. Smartphones serve as linking portals and interfaces for the analysis and display of results	Italy	Rateni et al. (2017)
		to store product-specific information	Greece	Nychas et al. (2016)
		Wireless Sensor Networks (WSN) and Radio Frequency Identification (RFID) are used for temperature monitoring	Spain	Badia-Melis et al. (2018)
		RFID planted in the live fish enables the monitoring of its movement and logistics	United Kingdom	Jacobsen et al. (2021)
Quality Management	Artificial Intelligence (Low utilisation)	A machine learning model to conduct a big-scale inspection	Taiwan	Chang et al. (2020)
		Deep learning is used to sort and classify the food to realise quality assessment and management		Jin et al. (2020)
	Blockchain (Low utilisation)	To manage the quality performance, enhance the management of the agri-food supply chain	United Kingdom	Zhao et al. (2019)
Interactive Communications	Augmented Reality (Low utilisation)	Supports inventory information, quick identification of ingredients, tools, processing facilities, identification of hazard	United States	Beck et al. (2016)
		Deep learning to improve monitoring	China	Zhou et al. (2019)
Legal requirement	Blockchain (Low utilisation)	Traceable, safe mechanism that enables trade participants to access details (document) in a timely manner	UAE	Juma (2019)
Hazard analysis	Blockchain (Low utilisation)	Blockchain integrated into the already proven structures of a HACCP system	German	Creydt and Fischer (2019)
	Artificial Intelligence (Low utilisation)	Deep learning to improve monitoring	China	Zhou et al. (2019)
	Sensors (Low utilisation)	Make critical decisions to ensure the safety of the products is not compromised	China	Xi et al. (2021)
Training	Augmented Reality (Low utilisation)	Conduct virtual training for food safety	United States	Clark et al. (2018)
Research and Development	Additive Manufacturing (Low utilisation)	Capable to foster product innovation and functionality	Australia	Godoi et al. (2016)
		Allowing businesses to quickly modify the level of integration	Brazil	Nascimento et al. (2019)

devices such as mobile phones, digital cameras, and sensors can collect and transmit data to centralised food safety data systems *via* Wi-Fi or other media Zhou et al., 2022. It is also notable that several other technologies such as big data, artificial intelligence (AI), additive manufacturing, and augmented reality showed high potential to create smart food safety practices, however, the evidence of their successful application is still very limited. AI can be used to build models with high accuracy to identify, predict and make decisions for dealing with complex food safety issues through two common concepts such as machine learning and deep learning (Jin et al., 2020). A great length of effort and research still needs to be done in expanding and innovating the usage of DI to improve the food safety programme.

TABLE 2 Opportunities of DI toward a sustainable food operation.

Technology	Economic	Environmental	Social	References
Blockchain	-Reduce transaction cost -Reduce cost and risk through digital payment -Increase revenue	-Advanced traceability helps to reduce resource consumption and waste	-Smart contracts eliminate the third trusted party -Ensure quality and safety of purchase for customers -Ensure public safety and avert corruption -Well-informed users	(Tripoli and Schmidhuber, 2018; Antonucci et al., 2019; Lezoche et al., 2020; Tiscini et al., 2020)
Internet Of things	-Decrease production costs -Minimize labor costs -Maximize profitability	-Optimization of resources efficiently (Water and energy) -Reduce waste -Prevent soil from deterioration	-Increase consumer satisfaction -Ensure Certification -Improve animal welfare -Minimize manual work and error	(Lezoche et al., 2020; Jagtap et al., 2021; Cook et al., 2022)
Big Data	- Improve yield -Reduce interaction cost	-Minimize waste and food loss - Effective use of resources -Reduce environmental footprint	-Improved customer service -Transition towards digital skills -Social media analytics	(Ahearn et al., 2016; Engelseth et al., 2019; Rejeb et al., 2021; Margaritis et al., 2022; Rejeb et al., 2022)
Artificial intelligence a	-Increase yield -Reduce operating cost -Improve forecasting	-Efficient management of resources -Reduce GHG emissions -Improve food quality -Minimize waste -Water footprint	-Reduce human intervention, effort, and error -Simply collaborate and improve trust	(Lezoche et al., 2020; Sharma et al., 2020; Santoso et al., 2021)
Autonomous robots	-Reduce production time and cost	-Reduce waste and GHG emissions	-Obtaining appropriate labor -Reduce manual labor	(Barbut, 2020; Duong et al., 2020; Hassoun et al., 2022)

3.4 Digital technologies for a sustainable food operation

FSC should integrate industry 4.0 technologies into its sustainability strategies (Lezoche et al., 2020). To deal with risks and uncertainties, digital solutions seem to be effective tools for real-time Although blockchain application was initially used to record financial transactions, its application has evolved for food safety purposes, particularly to ensure that data in the food production process will enable quick sharing of information such as origin, batch number, and manufacturing date, as well as accountability and honesty of manufacturing process, food safety certification, and organic products, which help to promote food safety and increase consumers' trust (Bacco et al., 2022). According to (Kumar et al., 2022), digital technologies such as big data (BD), blockchain, and the internet of things (IoT) enhance sustainability in the FSC (Bacco et al., 2022). In this section, we present the impacts of industry 4.0 technologies on economic, environmental, and social performance. Table 2 presents a summary of the opportunities the DI brings to food operations.

The traceability opportunity offered by blockchain is the most published article for sustainability as it allows customers to track their products from the beginning of the supply chain. Hence customers are reassured of the quality (source and freshness) and safety of the products (Zhao et al., 2019). While buying, consumers can verify product conformity through secure and fixed data using a QR code. An anti-corruption and fraud environment is settled due to data transparency, certifiability, and accountability (Tiscini et al., 2020). From an economic view, financial efficiency is improved through peer-to-peer transactions. In doing so, the cost and risk of the transaction are minimized due to the ability of the system to ratify payment without a third trusted party (Tripoli and Schmidhuber, 2018). Further, the high quality ensured by Blockchain certification rise the product value in the market, and hence price and revenues are affected positively (Tiscini et al., 2020). As for environmental benefits, the consumption of resources such as paper and food waste is reduced through advanced traceability (Feng et al., 2020). Namely, Blockchain proved its efficiency in waste minimization during food recalls (Krzyzanowski Guerra and Boys, 2022).

IoT increases consumer satisfaction by providing detailed product information in response to quality, safety, and sustainability requirements (Jagtap et al., 2021). According to (Musa and Basir, 2021), IoT tools and sensors can share real-time data effectively and increase yield. Further, IoT improves connectivity, productivity, and profitability (Hassoun et al., 2022). IoT supports the effective use of energy and water and controls waste generation through real-time monitoring (Cook et al., 2022).

The use of Big Data is required to counter the increasing complexity of FSC management to benefit from the generated data for effective decision-making support (Coble et al., 2018). Cost is minimized due to irrigation practices improvement based on data analysis. Green practices are supported, as such, soil is conserved, GHG emissions are minimized, use of chemicals and landfilling are avoided (Rejeb et al., 2021). Another use of BD is the analysis of customer opinions towards food quality and safety through social media (Singh et al., 2018). BD and IoT are used together to provide and track information in every part of FSC (Cook et al., 2022).

Artificial intelligence tools are requisite to transit toward a more sustainable food system (Camaréna, 2020). Among of the tools, sensing systems and machine learning algorithms increase productivity and yield (Chlingaryan et al., 2018). A positive impact is observed on yield production and nitrogen management while minimizing operating costs and environmental impacts through the sensing system (Sharma et al., 2020).

Autonomous robots are a necessary tool in industry 4.0 dealing with difficult, costly, and time-consuming labour operations (Hassoun et al., 2022). In the meat supply chain, automation increase efficiency, minimize manual operations, handle labor shortage and deal with skilled employees' availability (Barbut, 2020). According to Duong et al. (2020), waste and service time are reduced because of the application of autonomous robots in prediction and production management. Other technologies are improving sustainability in the supply chains such as cloud computing, cyber-physical systems, additive manufacturing, digital twins, and simulation.

Apart from cloud computing, the implementation of these technologies is still in its infancy in FSC (Smetana et al., 2021; Bacco et al., 2022; Hassoun et al., 2022). Mahroof et al. (2022) suggest that digital twins and simulation can reduce warehouse waste and costs, in addition to preparing managers for contingency planning. With additive manufacturing, new food sources can be added to meet customers' needs and 3D bioprinting reduces environmental impacts (Bacco et al., 2022). Smetana et al. (2021) consider that CPS are key engineering technology for a more nutritious and sustainable novel food system.

In fact, industry 4.0 technologies are interconnected and integrated collectively to achieve a secure, safe, and sustainable food system. Implementing different technologies leads to reduced operating costs, improved yield, and higher profitability. Moreover, sensing, tracking visualising and automating reduce the negative environmental impacts including waste, food loss, GHG emissions, and natural resources depletion. Being informed in real-time about product quality and safety, customer satisfaction and trust improved. Further, labor risks, errors, and manual efforts are shortened and evolved toward more highly digital skills. Notably, the literature places more emphasis on economics and less on environmental sustainability. IoT, big data, and blockchain are mostly applied to FSC sustainability. The literature shows that the goal before and post-Covid 19 pandemic in the food industry is still to protect the consumers by ensuring food safety across the FSC and minimizing food loss and environmental impact.

4 Conclusion and future research perspective

The review revealed several food safety and sustainability implications and areas deserving of future exploration in the post-pandemic era. Concerning practitioners working in the industry, the findings provide at least three levels of important insights. First, the literature synthesis explained how the COVID-19 pandemic may directly cause hazards across the food chain through food, but the rapid application of DI due to the pandemic can improve food safety practices and brings mixed effects towards sustainability of the supply chain in the post-pandemic era. Second, the presented research synthesized proposed digital technological clusters that are suggested to enable safer food and lastly linked individual technologies to their specific sustainability opportunities in the FSC.

In a nutshell, this work carries out the opportunity of DI in two important areas in a resilience FSC, which are sustainability and food safety. The COVID-19 event has intensified the discussion of how digital technologies can enable the resilience of a food system. Blockchain is the technology that has mostly expanded its usage towards food safety mainly due to its ability of data security towards traceability, monitoring, and inspection, and for sustainability (social and economic). The next promising technology is IoT-based solutions as most studies and implemented to improve the monitoring of food safety. The marriage of blockchain and IoT can be a frontrunner for traceability in the food system. The research highlighted that DI could help establish a sustainable food system. However, despite producing more than 70% of the world's food, cutting-edge DI in the food system is inaccessible to small businesses. Issues like data fairness (e.g. Findability, Accessibility, Interoperability, and Reusability (FAIR)), data quality, and lack of standardization make it a challenge for the usage of the DI in the food system.

Concerning future research directions, it is important to note that the areas of FSC risk management were well-developed areas of research long before the COVID-19 disruption, however the DI integration with FSMS may bring new opportunities. Based on the literature, four areas deserve future exploration;

- The lessons that can be learned from the pandemic era to mitigate issues in FSC, preparing for a future pandemic.
- The details assessment of the correlation of food safety and sustainable components with the digital technologies' clusters.
- Embedding people aspects within the DI system to guarantee food safety and sustainable FSC.
- The infrastructure which can meet all the requirements of the new technologies that are still lacking in the food safety system.

Author contributions

Conceptualization: SH-L. Data curation: AA and AC. Funding acquisition: SH-L. Investigation: SH-L and ZI. Methodology: SH-L and WD. Project administration: ZI and SH-L. Resources: SH-L and ZI. Software: WD. Supervision: SH-L. Visualization: HS. Writing—original draft: SH-L, ZI, and WD. Writing—review and editing: ZI, AA, HS, and AJ. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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