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COMPREHENSIVE REVIEW

From Food Industry 4.0 to Food Industry 5.0: Identifying technological enablers and potential future applications in the food sector

Abdo Hassoun[1,2] | Sandeep Jagtap[3,4] | Hana Trollman[5] | Guillermo Garcia-Garcia[6] | Linh N. K. Duong[7] | Prateek Saxena[8] | Yamine Bouzembrak[9] | Horst Treiblmaier[10] | Carlos Para-López[11] | Carmen Carmona-Torres[11,12] | Kapal Dev[13,14,15] | David Mhlanga[2] | Abderrahmane Aït-Kaddour[16,17]

[1]Sustainable AgriFoodtech Innovation & Research (SAFIR), Arras, France

[2]College of Business and Economics, University of Johannesburg, Johannesburg, South Africa

[3]Division of Engineering Logistics, Department of Mechanical Engineering Sciences, Faculty of Engineering, Lund University, Lund, Sweden

[4]Sustainable Manufacturing Systems Centre, Cranfield University, Cranfield, UK

[5]School of Business, University of Leicester, Leicester, UK

[6]Department of Chemical Engineering, Faculty of Sciences, University of Granada, Granada, Spain

[7]Bristol Business School, University of the West of England, Bristol, UK

[8]School of Mechanical and Materials Engineering, Indian Institute of Technology Mandi, Mandi, Himachal Pradesh, India

[9]Information Technology Group, Wageningen University and Research, Wageningen, The Netherlands

[10]School of International Management, Modul University Vienna, Vienna, Austria

[11]Department of Agrifood System Economics, Institute of Agricultural and Fisheries Research and Training (IFAPA), Granada, Spain

[12]Institute of Regional Development, University of Granada, Rector López Argüeta, s/n. 18071, Granada, Spain

[13]ADAPT Centre and Department of Computer Science, Munster Technological University, Cork, Ireland

[14]Department of Electrical and Computer Engineering, Lebanese American University, Byblos, Lebanon

[15]Centre for Research Impact & Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura, Punjab, India

[16]Unité Mixte de Recherche sur le Fromage UMRF, Université Clermont-Auvergne, INRAE, VetAgro Sup, Clermont-Ferrand, France

[17]Faculty of Agro-Industrial Technology, Universitas Padjadjaran, Sumedang, Indonesia

Correspondence
Abderrahmane Aït-Kaddour, Unité Mixte de Recherche sur le Fromage UMRF, Université Clermont-Auvergne, INRAE, VetAgro Sup, Clermont-Ferrand, France.
Email: abderrahmane.aitkaddour@vetagro-sup.fr

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Abstract

Although several food-related fields have yet to fully grasp the speed and breadth of the fourth industrial revolution (also known as Industry 4.0), growing literature from other sectors shows that Industry 5.0 (referring to the fifth industrial revolution) is already underway. Food Industry 4.0 has been characterized by the fusion of physical, digital, and biological advances in food science and technology, whereas future Food Industry 5.0 could be seen as a more holistic, multidisciplinary, and multidimensional approach. This review will focus on identifying potential enabling technologies of Industry 5.0 that could be harnessed to shape the future of food in the coming years. We will review the state-of-the-art studies on the use of innovative technologies in various food and agriculture applications over the last 5 years. In addition, opportunities and challenges will be highlighted, and future directions and conclusions will be drawn. Preliminary evidence suggests that Industry 5.0 is the outcome of an evolutionary process and not of a revolution, as is often claimed. Our results show that regenerative and/or conversational artificial intelligence, the Internet of Everything, miniaturized and nanosensors, 4D printing and beyond, cobots and advanced drones, edge computing, redactable blockchain, metaverse and immersive techniques, cyber-physical systems, digital twins, and sixth-generation wireless and beyond are likely to be among the main driving technologies of Food Industry 5.0. Although the framework, vision, and value of Industry 5.0 are becoming popular research topics in various academic and industrial fields, the agri-food sector has just started to embrace some aspects and dimensions of Industry 5.0.

KEYWORDS
advanced technologies, agri-food, fifth industrial revolution, human centricity, sustainability

1 | INTRODUCTION

Over the last years, the need to foster innovation, develop new technologies, and implement innovative solutions in the agri-food sector has become urgent due to the emergence and aggravation of a range of pressing challenges, such as climate change, the biodiversity crisis, and problems of food waste and plastic pollution, as well as the shortage of qualified food personnel and food workers due to the outbreak of armed conflicts and pandemics (Bahn et al., 2021; Senturk et al., 2023). To mitigate these complex multifaceted issues, significant advancements have recently enabled the emergence of a new scientific paradigm, known as the fourth industrial revolution (or Industry 4.0), which is spurred by high automation and digitalization and characterized by the integration of information and communication technologies with enhanced interconnection and real-time data exchange, offering new opportunities for achieving precision agriculture, smart farming, and smart food factories (Birkel & Müller, 2021; Hassoun, Marvin et al., 2023; Marvin et al., 2022; Sadeghi et al., 2022).

Although there have been a large number of studies and reports on Industry 4.0 in scientific literature, little has been published about Food Industry 4.0. A few recent articles have identified the main enablers of Industry 4.0 in agriculture and the food industry (Hassoun, Aït-Kaddour et al. 2023; Hassoun, Bekhit, et al., 2024; Hassoun, Siddiqui, et al., 2024; Javaid et al., 2022). Industry 4.0 is being driven by the deployment and leveraging of advanced technologies, especially (i) digital, such as artificial intelligence (AI), big data, blockchain, digital twins (DTs), and cloud computing; (ii) physical, such as smart sensors, robots, and drones; and the Internet of Things (IoT), and (iii) biological technological innovations, including recent advances in nanotechnology and biotechnology, such as precision fermentation and genetic engineering (Hassoun, Aït-Kaddour et al., 2023). However, Industry 4.0 is not a panacea and encompasses some limitations due to its technology-centricity, and profitability and productivity-focused features (Maddikunta et al., 2022; Nahavandi, 2019; Xu et al., 2021).

Nowadays, there is much discussion around the fifth industrial revolution (Industry 5.0). There are different opinions about Industry 5.0, which is still debatable whether it is an evolution of Industry 4.0 or a new revolution, albeit all agree upon the three main pillars of Industry 5.0, namely, human-centricity, sustainability, and resilience (Agote-Garrido et al., 2024; Barata & Kayser, 2023; Ivanov, 2023). Industry 5.0 has become a topic of enormous interest over the last years, especially in academic and scientific fields as can be noticed from the tremendous increase in the number of publications within the Scopus database (Figure 1).

There is no general agreement on Industry 5.0 enabling technologies. Nevertheless, advanced AI-based solutions, the Internet of Everything (IoE), collaborative robots (cobots) and advanced drones, miniaturized and nanosensors, 4D printing and beyond, edge computing, redactable blockchain, metaverse and immersive techniques, sixth-generation wireless (6G) and beyond,

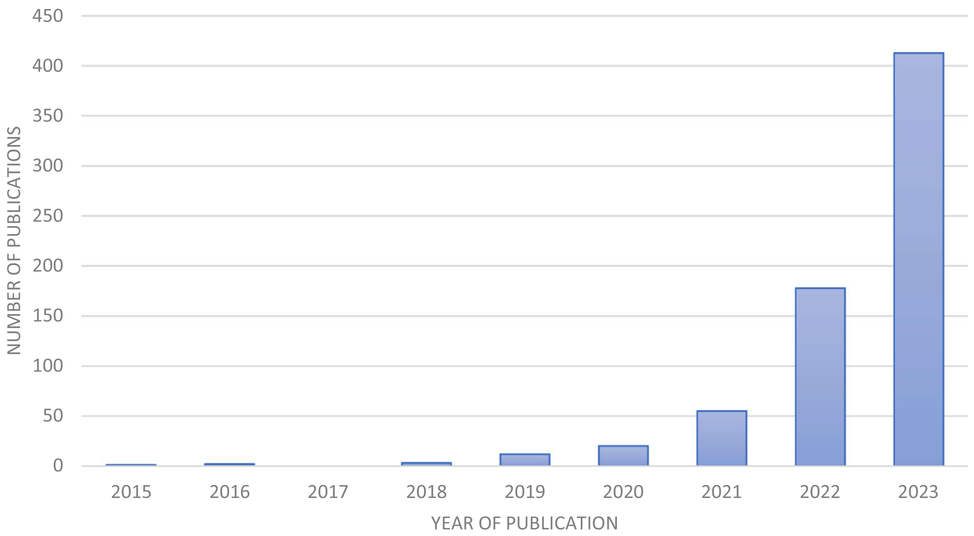


FIGURE 1 Evolution of the number of publications on Industry 5.0 from 2015 to 2023. *Source*: data were obtained from Scopus on March 5, 2024, using the following search query: Article Title: Industry 5.0 OR Fifth industrial revolution).

cyber-physical systems (CPSs), and DTs have been highlighted as potential enablers of Industry 5.0 (Huang et al., 2022; Mourtzis et al., 2022; Tallat et al., 2024; Xu et al., 2021).

Based on the previously mentioned references, Industry 4.0 and Industry 5.0 represent distinct stages in the evolution of industrial and technological advancements, each with unique (i) focuses, (ii) technological components, and (iii) objectives. Industry 4.0 primarily emphasizes the integration of CPSs, IoT, and big data analytics to enhance automation, digitalization, and productivity across manufacturing and other industries. It leverages a combination of digital technologies, such as IoT, AI, big data, cloud computing, and blockchain, alongside physical technologies like smart sensors, robots, and drones, and biological innovations, including precision fermentation and genetic engineering. The main objective of Industry 4.0 is to create “smart factories” where machines and systems are interconnected, enabling real-time data exchange and decision-making to maximize efficiency, reduce costs, and boost productivity.

In contrast, Industry 5.0 builds upon these advancements by introducing a more holistic and human-centric approach. It integrates technology with human creativity, fostering more sustainable and resilient production processes that prioritize both environmental and social well-being. Key technologies in Industry 5.0 include advanced AI, IoE, miniaturized and nanosensors, 4D printing, collaborative robots (cobots), edge computing, redactable blockchain, the metaverse, immersive techniques, 6G and beyond, CPSs, and DTs. The focus of Industry 5.0 is on enhancing collaboration between humans and machines, promoting sustainability, resilience, and the ethical use of technology, while reducing environmental impact. Although Industry 4.0 is predominantly technology-centric and driven by profitability, Industry 5.0 strives for a balanced coexistence of humans and advanced technologies, emphasizing sustainable practices and ethical considerations.

Although many publications have focused on the use of Industry 5.0 principles in various fields, such as supply chain (Frederico, 2021), healthcare environment (Javaid et al., 2020), logistics (Jafari et al., 2022), construction (Marinelli, 2023), education (Gürdür et al., 2022), economy (Elangovan, 2021), among others (Ghobakhloo et al., 2022; Khan et al., 2023), there is very little research in the agri-food sector. Indeed, to the best of our knowledge, the concept of “Food Industry 5.0” has not been introduced to the scientific literature yet. Therefore, this study aims to conduct a scoping review of various sources (including peer-reviewed literature and gray literature) in order to formulate a vision of Food Industry 5.0 and identify its enabling technologies in agriculture and the food industry.

2 | CORE PRINCIPLES OF FOOD INDUSTRY 5.0

The evolution from the first industrial revolution (Industry 1.0) to Industry 4.0 represents significant advancements in industrial and technological processes. Industry 1.0 began in the late 18th century with the advent of mechanization, steam power, and the establishment of factories, shifting economies from agrarian to industrial. This initial wave brought mechanized farming equipment, which increased agricultural productivity and efficiency.

Industry 2.0 emerged in the late 19th century, characterized by mass production, assembly lines, and the widespread use of electricity, revolutionizing manufacturing processes and increasing productivity. This era saw the development of refrigerated transportation and storage, transforming food preservation and distribution. After the mid-20th century, Industry 3.0 emerged, marked by the advent of automation through computers and programmable logic controllers, and the rise of information technology and electronics, further enhancing efficiency and precision. Automation in agriculture led to the use of GPS technology in farming, improving crop yields and resource management. Industry 4.0, emerging in the early 21st century, integrates CPSs, IoT, big data analytics, and advanced robotics, creating interconnected and intelligent systems that optimize production and enable real-time decision-making. In agriculture and the food industry, Industry 4.0 technologies have enabled precision farming, smart irrigation systems, and automated food processing, significantly enhancing productivity, reducing waste, and improving sustainability through data-driven insights and innovations (Babar & Akan, 2024; Hassoun, 2024a; Raja Santhi & Muthuswamy, 2023).

The terminology of Industry 5.0 first emerged at the CeBIT 2017 trade fair in Hannover, Germany (Shiroishi et al., 2018). Building upon the foundations laid by Industry 4.0, Industry 5.0 takes a significant leap forward by placing humans in enhanced roles and fostering increased participation (Mourtzis et al., 2022). The Food 4.0 approach ushered in a transformative era for the food industry, emphasizing improved connectivity among various elements, including machines, devices, humans, and sensors (Martindale et al., 2022). Despite the undeniable technological advancements of Food 4.0, challenges such as substantial initial investments and a shortage of skilled workers to navigate the complex systems have resulted in excessive automation and subsequent job losses. Moreover, the high energy consumption associated with operating advanced technologies and maintaining constant connectivity has raised concerns about sustainability. Data privacy and security issues have also become more prominent, as the integration of IoT and big data analytics increases the risk of cyber-attacks and unauthorized data access. Additionally, the focus on maximizing efficiency and productivity often leads to environmental degradation due to the increased use of non-renewable resources and the generation of waste. Moreover, the emphasis on technology-centric solutions can sometimes overlook the importance of human creativity and the need for ethical considerations in technological applications, resulting in a lack of social acceptance and resistance from stakeholders. To tackle these issues, the concept of Food 5.0 emerged, aiming to intertwine digital transformation with social development, ensuring that the benefits of this industrial revolution are widespread. It is important to note that Food 5.0 is not presented as an alternative to Food 4.0 but as a progressive step toward heightened automation and connectivity with a greater emphasis on human involvement (Elangovan, 2021; Tallat et al., 2024). Within the framework of Food 5.0, three core elements emerge as follows: human-centricity, sustainability, and resilience (Figure 2) (Ivanov, 2023). This approach envisions a future where technology serves as a catalyst for positive social and economic impacts, aligning industrial progress with the well-being and active participation of humanity.

2.1 | Human-centricity

In the realm of Food 4.0, the spotlight was on technologies geared toward optimizing food production processes, resulting in the implementation of automated solutions that significantly expedited and streamlined production. However, this progress came at the cost of job displacement, as machines took over tasks previously performed by humans (Martindale et al., 2022). In Food 5.0, the focus has shifted to the empowerment of humans through symbiotic collaboration with technology. The emphasis is no longer on replacing humans but on leveraging technology to augment human capabilities (Tallat et al., 2024). This paradigm shift has given rise to innovative solutions designed to enhance, rather than supplant, human involvement in various industries. A tangible example is found in the baking industry, where collaborative robots (cobots) work alongside humans to perform tasks like tray-up bagels and placing them in a trolley (Figure 3a) (El Zaatari et al., 2019). Additionally, augmented reality (AR) is being employed in factory settings, providing step-by-step instructions to assist humans in the maintenance of motors (Figure 3b) (Jagtap et al., 2021). As Food 5.0 unfolds, the overarching objective is to establish a symbiotic relationship between humans and machines.

In this coexistent ecosystem, each entity complements and enhances the capabilities of the other, fostering a harmonious collaboration that advances both technological innovation and human potential. The ultimate aim is to create a future where humans and machines coexist and thrive in a mutually beneficial partnership.

2.2 | Sustainability

In the era of Food 5.0, the overarching goal is to cultivate a sustainable ecosystem marked by heightened efficiency and reduced carbon footprints. To realize this vision, the food industry is embracing the principles of a

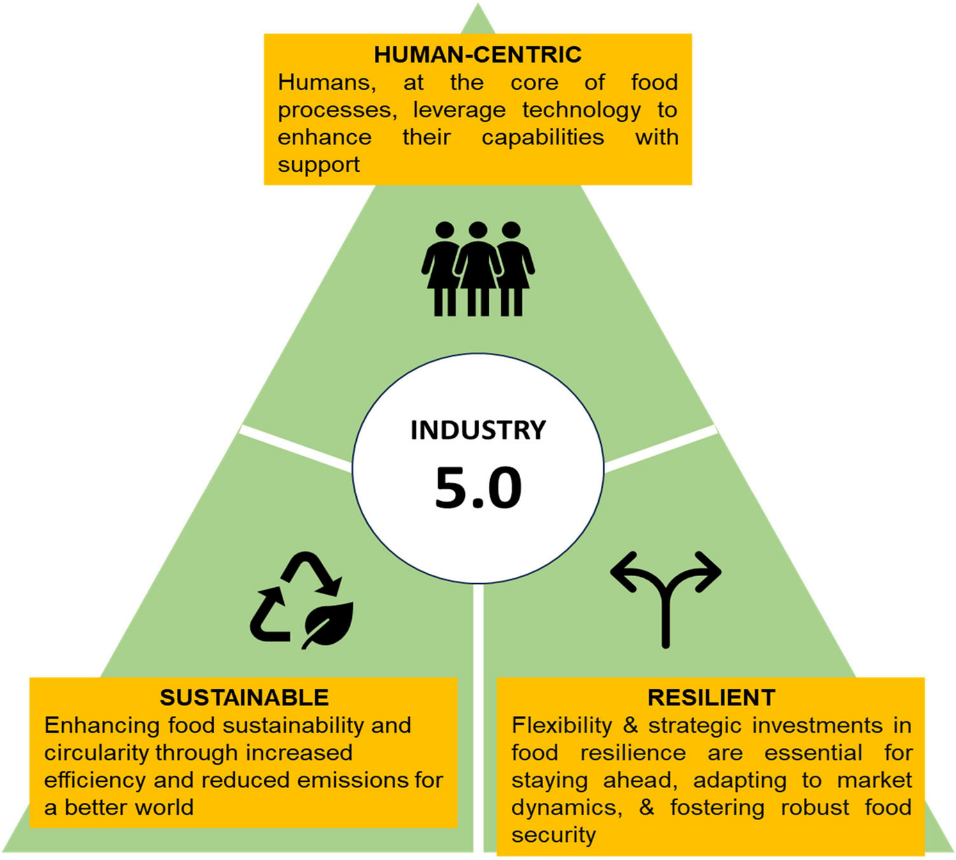
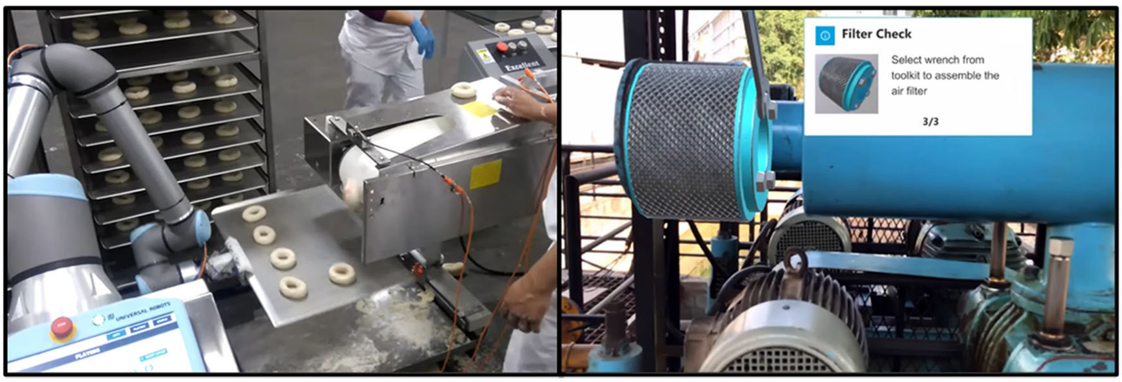


FIGURE 2 Core elements of Food Industry 5.0.



(a) (b)

FIGURE 3 Examples of Industry 5.0 implementation in the food industry a: Collaborative robots (Cobots) b: Augmented reality application for maintenance purpose).

circular economy and integrating sustainable practices into its operations. A pivotal aspect of this transformation involves adopting proactive measures to minimize or eliminate the generation of food waste (Sikder et al., 2023). Within this paradigm, the focus extends beyond waste reduction to innovative approaches for repurposing waste. Should waste be unavoidable, strategies are implemented to transform it into resources fit for human consumption, animal feed, or energy production. A compelling example is evident in dairy plant waste management, where discarded materials undergo processes to extract valuable whey proteins. Alternatively, the waste can be directed to nourish black soldier fly larvae, yielding insect proteins suitable for both human and animal consumption (Hassoun, Tarchi, Aït-Kaddour, et al., 2024). In the absence of these options, the waste becomes a valuable resource for biofuel generation. Recognizing that the food sector is a significant consumer of water and energy, there exists immense potential to enhance sustainability through various environmental initiatives, promoting resource efficiency. Governments worldwide are actively engaging in regulatory and incentive-driven frameworks to steer the industry toward a sustainable trajectory, aiming to curtail emissions and foster responsible choices within the food production and supply chain. This collective effort underscores a commitment to a more meaningful and sustainable future, aligning with the principles of Food 5.0.

Industry 5.0 promotes the use of renewable energy sources such as bioenergy derived from algae. Advanced bioenergy systems can achieve a net positive energy balance, especially when wet extraction methods are used, as they require significantly less energy than traditional methods. This approach not only reduces the dependency on fossil fuels but also cuts down greenhouse gas emissions, contributing to a more sustainable environment. For example, it was reported that the use of a bio-refinery optimized with Industry 5.0 technologies can automate algae growth and harvesting systems, reducing operational costs and energy consumption by up to 30%–40%. Furthermore, Industry 5.0 technologies can improve the management of resources and waste. Indeed, the integration of IoT in bio-refineries allows for real-time tracking and forecasting of algae growth, optimizing the use of nutrients, and minimizing waste. This precise control over production processes can lead to a reduction in waste by up to 20%–30%, as indicated by the sensitivity analyses of algae yields and oil content (El Far et al., 2021). Another similar study showed that Industry 5.0 significantly enhances energy efficiency and sustainability in bioethanol and L-lactic acid production from red macroalgae cellulosic residue (Wong et al., 2022). Specifically, the implementation of a heat exchanger network synthesis generated a total energy savings of 35%. Additionally, the combined heat and power plant supply up to 70% of the plant's total electricity requirement. These advancements highlight the potential of Industry 5.0 to reduce energy consumption and promote sustainability in industrial applications.

2.3 | Resilience

Resilience, often defined as the capacity to rebound from adversity, holds a crucial role in navigating and mitigating disruptions (Williams et al., 2017). In a world characterized by uncertainties like war, terrorism, the ongoing Russia-Ukraine conflict, and the current Israeli war on Gaza, as well as the aftermath of the Covid-19 pandemic, the vulnerability of global food supply chains to such shocks is starkly evident (Agrawal et al., 2024; Hassoun et al., 2024; Jagtap et al., 2022; Mahroof et al., 2024). External calamities, ranging from climate change and floods to droughts and earthquakes, pose persistent threats. The recent and historical instances of crises underscore the fragility of global food supply chains, exposing them to the risk of significant disruptions, resulting in acute shortages of both food and labor (Jagtap et al., 2024). The consequences of these disruptions extend far beyond economic implications, affecting the safety and security of the global food system. Amid these challenges, the food industry now possesses powerful tools, including IoT, big data analytics, and real-time visibility. These technologies empower stakeholders to respond swiftly and effectively to disruptions, offering a dynamic and adaptive approach to supply chain management (Misra et al., 2022). Investing in enhancing the resilience of the food sector through these technological advancements holds the promise of not only safeguarding against unforeseen disruptions but also ensuring the safety and security of the global food supply. In essence, the call to invest in food resilience is a call to fortify our capacity to withstand and overcome shocks, thereby fostering a future where food safety and security prevail in the face of an ever-changing and unpredictable world.

3 | FROM FOOD INDUSTRY 4.0 TO FOOD INDUSTRY 5.0

3.1 | From traditional AI to regenerative conversational AI

AI combined with human expertise is considered to have significant potential as a driving force for improved global food security (Ben Abdallah et al., 2023; Guruswamy et al., 2022). Our understanding of AI continues to evolve, creating discrepancies in AI terminology and categorization (IBM Data and AI Team, 2023). Current AI classification based on capabilities includes Weak or Narrow AI, Strong or General AI, and Super AI (Figure 4), with the last two classes being theoretical.

All AI of today is Weak AI, meaning that training will enable it to perform a single or narrow task, usually with greater efficiency than a human. Current AI classification based on functionality includes Reactive Machine AI, Limited Memory AI, Theory of Mind AI, and Self-Aware AI. Weak AI includes the first two functional categories: reactive machines that only work with currently available data because they have no memory, and which rely on

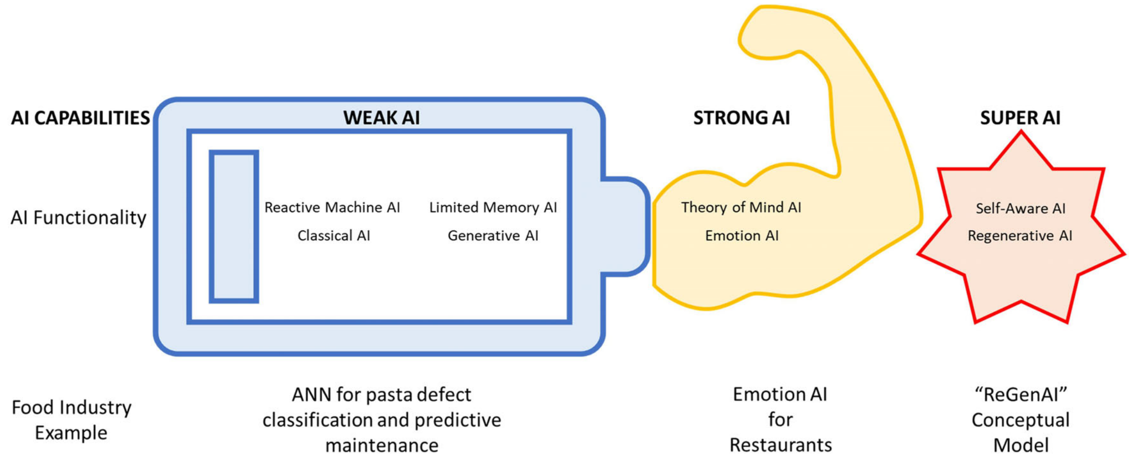


FIGURE 4 AI classified according to capabilities and functionality with food industry examples.

performing statistical operations on vast amounts of data; and limited memory AI that can use past and current data to yield a course of action most suited to achieving a desired outcome.

Industry 5.0 learning systems based on Artificial neural network are proposed for processing pasta images and predictive maintenance as part of workflow control (Massaro & Galiano, 2020). Emotion AI may improve restaurant customer satisfaction as reported by Loman.ai company in 2024 (https://www.loman.ai/). "ReGenAI" is a conceptual model for consumer-centric, regenerative AI applicable to grocery retailing.

Weak AI applications in food industry include computer vision: image recognition and classification, object tracking and detection, and content-based image retrieval; robotics for materials handling, assembly, and quality inspections; and expert systems that can be trained on data to solve complex problems: uncovering trends and patterns to aid decision-making.

Strong AI includes Theory of Mind AI that would have the functionality of understanding the thoughts and emotions of other entities, for example, inferring human motives and reasoning to personalize interactions; understanding and contextualizing work (images, text, and so on), which current generative AI tools are incapable of.

Self-Aware AI would possess Super AI capabilities, giving it the ability to understand its own internal conditions and have its own set of emotions, needs, and beliefs. Such cognitive AI would take advantage of further developments in natural language processing, data mining, and pattern recognition to better understand the world, leading to the emergence of regenerative or self-healing AI (Ghobakhloo et al., 2023). The concept of regenerative AI has been introduced for food retail as an AI that continuously learns, adapts, and improves with full awareness of users and their specific operational contexts, with one of the main differentiating factors from generative AI being an ability to influence future demand at the level of individual grocery shoppers (Zwanka & Zondag, 2023). Recently, there has been an enormous interest in ChatGPT (a type of conversational AI) for promoting further development and employment of AI in various fields (Javaid et al., 2023; van Dis et al., 2023).

AI in agri-food industry—AI utilized in combination with blockchain and other technologies may aid agri-food supply chains in becoming more human-centric in line with Industry 5.0 objectives (Ahamed & Vignesh, 2022). Digital technologies can help prevent food spoilage, reduce food waste, and ensure food safety, supporting environmental sustainability as well as being human-centric. All agriculture-related processes from machinery to decision-making systems are amenable to the ongoing digital revolution (Konfo et al., 2023). AI may be used to automate tasks, forecast crop yields, and improve productivity by, for example, optimizing irrigation scheduling and providing real-time monitoring of weather conditions and soil moisture levels for customized recommendations at the level of individual farms (Pandey & Mishra, 2024; Polymeni et al., 2023; Sharma, Jain et al., 2021). For example, IBM and Yara have developed a comprehensive digital farming platform that combines unrivalled agronomic knowledge with the power of AI and data analytics to provide hyper-local weather insights for smallholder farmers (Rylander, 2021).

A recent study showed that the implementation of AI-driven irrigation systems can lead to significant water and energy savings (Preite & Vignali, 2024). Indeed, AI-based predictive algorithms in irrigation management systems have demonstrated the potential to save up to 27.6% of water and 57% of energy compared to traditional irrigation practices. This substantial reduction is achieved by optimizing irrigation schedules, preventing overwatering, and ensuring that soil moisture levels are maintained within optimal ranges.

AI in food manufacturing—The Adaptive Smart Factory (ASF) concept envisions a transition from traditional production systems to highly automated, flexible, digitalized, and resilient production systems (Ghobakhloo et al., 2023). Such ASFs would take a human-centric approach to manufacturing, benefiting the human workforce by using technology adaptations in production processes while responding to changes in consumer behavior or market dynamics. A process-product innovation model for food manufacturing small- and medium-sized enterprises to adopt Industry 5.0 has been proposed on the basis of the incorporation of agile strategy and Society 5.0 (Saptaningtyas & Rahayu, 2020). Such a process reengineering approach has been specifically applied to the design of pasta production processes (Massaro & Galiano, 2020). The estimated main benefits of introducing process reengineering in the pasta production process are a 20% production increase, a 40% decrease in raw material waste, an 80% decrease in costs of machine maintenance, a 90% decrease in production failure risks, and a 60% increase in pasta quality.

Quality control is an important aspect of ASFs, posing both opportunities and challenges (Nguyen et al., 2023). AI can improve process mapping by suggesting optimized subprocesses and defining risks related to production and product quality. A theoretical model of process mining, integrating a decision support system based on supervised and unsupervised algorithms, has been proposed—the latter with application to a food roasting process (Massaro, 2022). The achievement of high sustainability standards is dependent on improving the technical-scientific quality of production systems. Consequently, AI has been adopted to improve energy efficiency in a food ingredient company while empowering people in the process to achieve better outcomes and further the Industry 5.0 aim of improving sustainability (Redchuk et al., 2023). The specific case of aging society has also been studied in the context of Industry 5.0 in the bakery industry, presenting a decision-making tool to help managers identify the most appropriate strategy for avoiding corporate amnesia (Leon et al., 2024) that could be facilitated by AI in the future.

AI in food supply chain—Supply chains are being transformed by Industry 5.0 from being rigid and linear to instead becoming agile, modular, and scalable interconnected digital networks. AI, machine learning (ML), and deep learning are all trending topics in Supply Chain 5.0 literature with human-centric supply chains, sustainable supply chains, and resilient supply chains supporting the conceptual framework, as shown in Figure 5 (Lazzaris et al., 2022; Villar et al., 2023).

Customer insights and real-time data are expected to enhance resilience to shocks such as the Covid-19 pandemic and the war in Ukraine. Smart logistics will include predictive delivery management systems, smart warehousing, intelligent shelves, and smart containers (Ding et al., 2021). A human-centric delivery plan for a distributed network of vending machines aligned with the concept of Industry 5.0, intended to mitigate shocks such as the Covid-19 pandemic by enabling uninterrupted deliveries and satisfying consumer preferences, has been proposed using state-of-the-art ML models (Grzegorowski et al., 2023).

Challenges to implementation of Industry 5.0 include the lack of a strategic roadmap, government support, management support, and technological skill in the agri-food industry, among others (Kankekar et al., 2023). A wider application of AI is facing many obstacles such as data availability, complexity, and heterogeneity, as well as ethical questions (Kabir & Ekici, 2024; Manning et al., 2022). AI-based solutions are commonly integrated with other Industry 4.0 and Industry 5.0 technologies (such as robotics and cobots, drones, and blockchain). For example, the integration of AI with blockchain would support food quality control, resolving food safety concerns (Charles et al., 2023), yet blockchain application is deficient in government regulation, and the implementation of AI requires skill levels that are rare in agri-food industry.

Future directions—Future research directions for AI that have potential applications in agri-food industry include cognitive computing for complex problems (Adel, 2022), sentiment analysis (Espina-Romero et al., 2023), human-machine collaboration (collaborative intelligence) providing, for example, improved marketing strategies that reduce waste and overproduction (Alojaiman, 2023), autonomous learning systems that self-program, self-organize, and self-optimize in support of human-centricity, AI-based management systems, DTs supported by rapid-response AI algorithms, and proactive human-robot collaboration (Leng et al., 2022).

Specific advanced applications of Industry 5.0 designed to address complex agri-food problems supported by AI are rare in the literature and await real-world trials. A multi-agent system relying on AI and edge computing has been designed as an alternative consumer-based price-making mechanism to mitigate food speculation while improving the sustainability of agricultural production (Trollman et al., 2023). Feature extraction (AI input) for the prediction of food supply chain failure modes (complex causality) combining human expertise with AI has been proposed alongside a framework for implementation (Trollman, 2024).

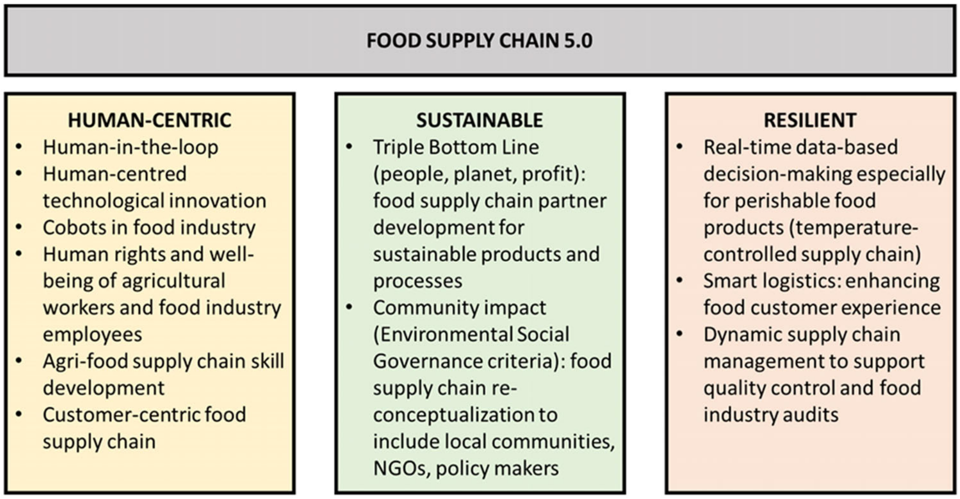


FIGURE 5 Food Supply Chain 5.0 conceptual framework.

3.2 | From the Internet of Things to the Internet of Everything

The IoT has profoundly transformed industrial processes as well as the use of digital technologies by the general population. IoT is a network of connected devices that collect and transmit data between themselves. These capabilities have been used in the food sector in recent years to optimize operations throughout the food supply chain (Hassoun, Jagtap, Garcia-Garcia, et al., 2023; Hassoun, Jagtap, Trollman, et al., 2023; Jagtap et al., 2020). However, a new technological concept has emerged that could lead to major changes in the industry: the IoE. IoE was first defined by Cisco company (2013) as the networked connection of people, processes, data, and things. Although IoT only refers to the connection of devices ("things"), IoE goes further by integrating devices, people, processes, and data. Therefore, although IoT only considers the connection between devices (i.e., machine to machine), IoE also considers other important connections, such as machine to people and people to people (Figure 6). Consequently, IoE is not a revolutionary idea, but rather the evolution of the IoT concept.

Due to the complexity of the IoE concept, da Costa et al. (2021) proposed a taxonomy to classify sensors, attributes, and characteristics in IoE applications. This is based on 4 categories (knowledge, type, observation, and capabilities), 18 dimensions, and 50 applications. The use of this taxonomy is useful to identify challenges and applications of IoE in a specific sector, for example, the food sector. However, a search of the existing literature concluded that the application of IoE in the food sector is very scarce. This section describes the possible applications of IoE in the following areas relevant in the food sector: logistics, agriculture, traceability, quality control, and sustainable production. The few articles that have addressed IoE applications in these areas are described.

Most studies that have considered the application of IoE in the food sector have investigated its use in logistics operations. IoE can help address some of the key challenges in conventional logistics management systems, such as lack of real-time information and low safety factor (Zhan et al., 2022). Numerical results demonstrated that IoE-based smart logistic network achieved superior performance metrics with an accuracy ratio of 92.1%, an investment efficiency of 98.4%, a demand forecast accuracy of 95.4%, a product delivery efficiency of 97.6%, and a network security rating of 96.4%. Wu et al. (2023) developed an architecture using IoE and DT technologies and applied it to cold chain logistics. Almalki (2020) tested the application of IoE-connected drones to track production, warehouse management, and logistics operations. Yang et al. (2023) developed and trialed an IoE system in perishable supply chain logistics to ensure minimal delays and quick response times in sensor data acquisition, authentication, consistency, and transparency within cold supply chain logistics.

On farms, IoE-connected sensors can be used to monitor soil conditions, weather, and crop health in real time. Data that can be collected include temperature, light, moisture, nutrients, pesticides, fertilizers, contamination and pollution, and the presence of pests. Examples of these applications include the work of Mohapatra and Rath (2022), who designed a sensor-based soil quality monitoring method based on IoE, and Suresh Kumar et al. (2021), who stored the collected data by an IoE system implemented on farms in the cloud. A similar approach can be used to manage livestock by collecting data on feeding patterns, well-being, location, and disease outbreaks.

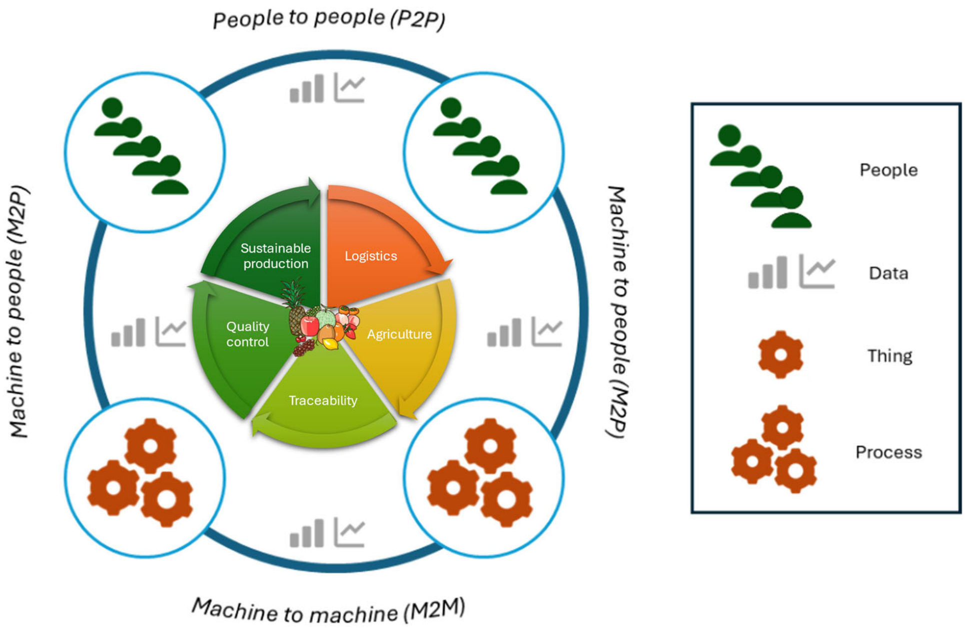


FIGURE 6 Connections in the Internet of Everything.

Live and automated recording and sharing of data can significantly improve the traceability of food operations, which is critical in the food sector. Accurate information can be accessed by all stakeholders at any time, building trust and transparency and reducing fraud. IoE can also be combined with other modern technologies, such as blockchain, to store collected data more efficiently and securely (Gayathiri, 2024; Joy et al., 2023). However, the food sector has been slow to embrace the benefits of connecting elements to the internet (Raheem et al., 2021). Food businesses have an opportunity to modernize their traceability operations and gain a competitive advantage by implementing IoE principles (Guruswamy et al., 2022).

The quality and safety of all operations in the food supply chain, as well as the final food products and their raw materials, can be better managed with an IoE system. If a food quality or safety parameter goes outside its defined threshold, an alert can be issued to alert staff to swiftly correct the error. For instance, Almalki (2020) used IoE-connected drones for food quality and safety purposes. Yang et al. (2023) combined an edge-cloud blockchain and IoE-enabled platform to improve quality management of perishable products.

By optimizing operations throughout the supply chain, the food sector becomes significantly more efficient, particularly in reducing food waste levels. This directly enhances the sustainability of food systems by minimizing resource wastage and promoting more effective utilization of food products. Some applications have been proposed for managing urban waste (Malini et al., 2022) and reducing wastewater levels (Reddy et al., 2021). It is now imperative to apply similar approaches to address food waste. Another way to do so is to better forecast food demand and adjust production accordingly. This would require a better understanding of consumer behavior, for example, by more accurate marketing based on IoE (Nozari et al., 2021).

The transition from IoT to IoE is poised to revolutionize many sectors of agriculture and the food industry. Although IoT has already optimized operations by connecting devices to enhance efficiency, IoE expands this by integrating people, processes, data, and things. This comprehensive network can address key challenges in logistics, agriculture, traceability, quality control, and sustainable production. Despite its potential, the application of IoE in the food sector remains scarce. However, existing studies highlight its benefits, such as improved logistics performance, real-time monitoring of agricultural conditions, and enhanced food traceability and quality management. Embracing IoE can lead to significant reductions in food waste, better resource utilization, and a more sustainable food system. It is crucial for the food sector to adopt IoE technologies to modernize operations and gain competitive advantages.

3.3 | From smart sensors to miniaturized, nano, and hyper-intelligent sensors

A sensor is a device capable of detecting, locating, or quantifying energy or matter followed by producing a signal for the detection or measurement of a physical or chemical property to which the device responds (Müller & Schmid, 2019). A sensor typically consists of two components: receptor and transducer. The first component serves to detect the presence, activity, composition, or concentration of certain chemical or physical analytes. This physical or chemical information is then converted into a form of energy that can be measured by the transducer. The measured signal is further converted into a useful analytic signal, which can be an electrical, chemical, optical, or thermal signal (Mlalila et al., 2016).

Recent technological advancements ushered in by Industry 4.0 have revolutionized ordinary sensors, transforming them into sophisticated smart sensors. Smart sensors and biosensors boast numerous features, including compact size, low cost, reduced power consumption, and self-diagnostic and identification capabilities. This transformation has been particularly accelerated by recent progress in materials science and nanotechnology, leading to the emergence of miniaturized and nanosensors (Garg et al., 2024; Grabska et al., 2024; Hassoun, Boukid et al., 2023; Javaid, Haleem, Singh, et al., 2021; Kalsoom et al., 2020; Nam et al., 2022).

In agriculture and the food industry, the integration of diverse types of sensors with IoT and other monitoring devices enables to collect and process data in real-time (Rajak et al., 2023; Turgut et al., 2024; Ullo & Sinha, 2021). This approach allows food producers and manufacturers to evaluate raw material composition and nutrient levels during production and processing, enabling informed decisions on product acceptance, rejection, or specific processing routes. Additionally, it allows for adjustments or modifications to production parameters or process variables to align with raw material characteristics and take preventive and corrective actions (Hassoun, A.; Aït-Kaddour, A.; Dankar et al., 2024; Javaid, Haleem, Pratap Singh, et al., 2021; Kamalapuram & Choudhury, 2024).

For example, smart sensors based on spectroscopy and hyperspectral imaging can be used to detect moisture levels, fat content, and protein distribution in seafood and meat processing, allowing for precise control over product quality and minimizing the yield loss (Jia et al., 2022; Wold et al., 2024). Similarly, these advanced techniques can assess the ripeness and sugar content of fruits, facilitating optimal harvest times and processing conditions (Wilson, 2021). These spectroscopic techniques provide detailed insights into the composition and quality of raw materials, enabling manufacturers to make informed decisions and swiftly address any anomalies detected during processing. This proactive approach not only optimizes resource use but also enhances the overall efficiency and sustainability of food production processes. By leveraging these intelligent systems, manufacturers can maintain ambitious standards of food safety and quality, adapting swiftly to any anomalies detected during processing (Chen et al., 2024; Hassoun, Anusha Siddiqui, et al., 2024). In precision agriculture and smart farming, smart sensors, coupled with AI and other Industry 4.0 technologies, are increasingly being utilized to achieve significant benefits in agriculture and food production. These sensors provide real-time data on various parameters such as soil moisture, temperature, humidity, and crop health, contributing to more sustainable and efficient agricultural practices, enhancing productivity while conserving resources (Morchid et al., 2024; Pandey & Mishra, 2024; Soussi et al., 2024).

Further advancements have led to the emergence of the concept of "Food Sensors 5.0," inspired by Industry 5.0, which aims to further improve the profitability and efficiency, while enhancing sustainability, reducing environmental footprint (e.g., decreasing energy consumption, extending products shelf life), and increasing synergy with humans (employees and consumers).

This progression has also led to the development of hyper-intelligent sensors, which combine advanced AI, real-time data processing, and enhanced connectivity to provide unparalleled precision and insight into food quality, safety, and supply chain management. These sensors enhance the resilience of the food industry by enabling swift responses to disruptions, ensuring consistent quality, and maintaining robust supply chains even in the face of unforeseen challenges.

Increased synergy and interaction among sensors, humans, and food products are paving the way for realizing the human-centric pillar of Food Industry 5.0. One approach to achieving this goal is the integration of sensors into smartphones, to enhance the management of food throughout the supply chain and empower consumers to make informed purchasing decisions.

Smartphone technology has advanced rapidly, driven by significant improvements in low-power processors, operating systems, user interfaces, displays, memory, and communications technology. This progress has led researchers to adapt smartphones for analytical measurements in food monitoring and quality evaluation (authentication, fraud detection), representing a significant step toward achieving the dream of handheld devices (Grabska et al., 2024; Ma, Wang et al., 2022).

The coupling of novel sensing technologies with smartphones has enabled the development of powerful lab-on-smartphone platforms, which have multiple applications in food analysis, including the detection of food adulteration, contaminants, toxins, pathogens, and allergens, among others (Magarelli et al., 2023; Shan et al., 2023). The integration of smartphones with various sensitive and selective biosensors has led to the development of portable and user-friendly analytical devices, offering low-cost and effective solutions for food quality and safety authentication (Chen et al., 2024; Doğan et al., 2024; Meliana et al., 2024).

Generally, sensors are made from ceramic substrates or non-degradable plastic polymers of chemical products derived from petroleum. However, sustainable materials are increasingly being investigated to fabricate new generations of Sensors 5.0, thereby fulfilling the sustainability requirement of Food Industry 5.0. For example, Teixeira et al. (2023) developed a wearable screen-printed electrochemical sensor integrated into the sustainable cellulose acetate substrate to quantify carbendazim and paraquat pesticides with a detection limit of 54.9 and 19.8 nM, respectively. The study demonstrated that the sensor could be attached on any type of agricultural product or food samples, such as leaves, vegetables, and fruits, for decentralized and on-site analysis that can be extended to many other agrochemical compounds. Moreover, battery-free and self-powered sensors can exhibit higher sustainability and advantages over the conventional sensors because they eliminate the maintenance of batteries on a regular basis, reduce the wastage of time caused by battery replacement, and reduce their lifetime maintenance cost. A battery-free wireless moisture sensor system (BWMS) coupled with near field communication reader was devised to monitor self-life of fruits. BWMS can acquire weight and temperature sensor data in real time from fruits and predict self-life to indicate quality of the fruit (Xiao et al., 2022).

3.4 | From robots to cooperative robots (cobots) and advanced drones

Industry 4.0 revolves around the integration of advanced digital technologies and AI into operational aspects, blurring the boundaries between human and non-human components (Jiao et al., 2020; Moeuf et al., 2020). These features of Industry 4.0 have led to the development of a new generation of collaborative robots, known as cobots, capable of sharing workspace with human operators (Hashemi-Petroodi et al., 2021). This new generation aims to combine human intelligence, creativity, and flexibility with robot's speed and accuracy. Cobots offer the abilities to enhance flexibility and automation in assembly lines, leading to reduced human workforce expenses and the execution of repetitive or tedious tasks typically performed by humans (Lv et al., 2022). Cobots also prove advantages in disassembly operations, particularly in managing the uncertainty surrounding the frequency, quantity, and quality of products (Huang et al., 2021).

As we transition into Industry 5.0, the focus shifts toward more advanced robots and cobots that not only work alongside humans but also integrate seamlessly into human-centric processes. This new phase emphasizes the synergy between human creativity and robotic precision, aiming to create smarter, more adaptive production environments that cater to evolving consumer needs and sustainability goals (Zafar et al., 2024).

Cobots have been adopted across various workstations performing a range of activities, including picking, packing, assembling, palletizing, welding, material handling, part and product inspection, machine loading/unloading, part cleaning, bin picking, and kitting (Jacob et al., 2023; Kana et al., 2021; Malik & Brem, 2021). The most common environment that has adopted cobots is the assembly environment (Guo et al., 2020).

In the food industry, cobots are being adopted in many sectors, such as food service (Pereira et al., 2022), food catering (Accorsi et al., 2019), and food manufacturing (Grobbelaar et al., 2021). Romanov et al. (2022) reviewed the adoption of cobots in meat processing and found that cobots help to enhance higher standards in human-working conditions and food safety and make automation more affordable for many businesses, particularly small businesses. In labor-intensive working environments, such as food industry, cobots support food businesses to improve the efficiency and the effectiveness of manufacturing (Ronzoni et al., 2021).

However, the adoption of cobots faces many challenges, and no single robotic solution can meet all the needs of food businesses. Therefore, customization and user feedback are essential for effective cobot implementation. A significant challenge relates to the dynamic relationships within the food industry, particularly in the food service sector (Pereira et al., 2022). Another common safety risk associated with cobots in food manufacturing is the improper use of unsafe tools, which can compromise the built-in safety features of cobots. For example, using a sharp tool can bypass the cobot's potential force limitation, posing a significant hazard. This often arises due to insufficient training of operators (Duong et al., 2020). The open-space environment in the food industry heightens the risk of untrained personnel approaching cobots or entering their operational areas. This can lead to potential injuries and decreased operational efficiency due to frequent stops or the need for cobots to replan their movement paths. These challenges underscore the importance of strategically determining the appropriate locations and methods for deploying cobots in the food industry, ensuring both safety and optimal performance.

The evolution of drones from Industry 4.0 to Industry 5.0 represents a significant leap in their capabilities and applications, particularly in the agri-food sector. Under Industry 4.0, drones have been primarily utilized for precision agriculture, leveraging advanced digital technologies such as AI, IoT, and robotics to enhance operational efficiency. Drones equipped with sensors, cameras, and GPS systems are used for tasks like soil analysis, crop health monitoring, and weather pattern analysis. This allows farmers to make informed decisions regarding irrigation, fertilization, and pesticide application, thereby optimizing resource utilization and improving crop yields. The focus has been on automating farming processes to reduce labor requirements and streamline operations (Mahroof et al., 2024; Rejeb et al., 2022).

With the advent of Industry 5.0, the role of drones has evolved to emphasize human-centric and sustainable approaches. Industry 5.0 drones are designed to facilitate seamless interaction between humans and technology, creating value through enhanced collaboration. These drones not only collect data but also assist in real-time problem detection and solution implementation, thereby preventing potential escalations and reducing management costs. For instance, the integration of drones with IoT enables precise mapping and monitoring of soil moisture and ambient environmental conditions, which supports timely interventions and promotes sustainable farming practices (Hayajneh et al., 2024; Victor et al., 2024).

Despite the advancements, the adoption of drones in agriculture faces challenges such as high costs, lack of technological awareness, and the digital divide. However, the potential benefits, including improved productivity, energy savings, cost efficiency, and better supply chain management, make continued research and development in this field imperative (Chin et al., 2023; Rejeb et al., 2022). The evolution from Industry 4.0 to Industry 5.0 highlights a shift toward more resilient, sustainable, and human-centric agricultural practices, showcasing the transformative potential of drones in modern agriculture. To sum up, drones have evolved from tools for precision agriculture in Industry 4.0 to key components of a human-centric, sustainable agricultural paradigm in Industry 5.0, driving significant improvements in efficiency, sustainability, and operational effectiveness in the agri-food sector.

3.5 | From 3D food printing to 4D and 5D printing

Food printing, popularly referred to as 3D food printing, has revolutionized the world of food production by creating long-lasting edible products from edible materials. The initial concept of food printing primarily focused on the visual appeal of food products, but as technology has advanced, the focus has shifted toward enhancing the taste, texture, and nutritional content of the printed food (Le-Bail et al., 2020; Lisovska & Harasym, 2023; Teng et al., 2022). This evolution has paved the way for 4D and 5D food printing technologies, which not only consider the visual and sensory aspects of food but also incorporate elements of customization, self-assembly, and responsiveness to external stimuli (Piyush et al., 2020; Teng et al., 2021).

One crucial aspect in the development of food printing technology is rheology. Rheology helps to determine the viscosity and consistency of the printable inks, which directly affects the quality and accuracy of the printed food (Srivastava et al., 2023; Tejada-Ortigoza & Cuan-Urquizo, 2022). By ensuring that the printed food maintains its desired shape, texture, and structural integrity during and after the printing process, rheology grants users control over the food printing process, facilitating the creation of intricate and complex structures. Moreover, rheological properties influence the printing speed, resolution, and overall printability of the food ink or material (Cheng et al., 2022). By understanding the rheological properties of food materials, the printing parameters can be optimized for 3D printing process. AI and ML can also be integrated for the 3D food printing at this step. Such algorithms can analyze vast amounts of data on rheological properties, printing parameters, and desired outcomes to optimize the food printing process, leading to improved precision and efficiency. These algorithms can also adapt and learn from previous printing experiences, allowing for continuous improvement and refinement of the printing process. Furthermore, the use of AI and ML can also help in recipe development, as these algorithms can analyze the sensory characteristics and nutritional composition of various ingredients to suggest optimal combinations for printing (Choi et al., 2023).

Overall, 3D printing fosters a sustainable approach by optimizing resource use and promoting circular economy practices. 3D printing technology can significantly reduce food waste through several innovative approaches. First, it enables precise production of food items, which means that only the exact amount of ingredients needed is used, minimizing excess and leftovers. This on-demand production approach can lead to a significant reduction in food waste in some applications. Additionally, 3D printing allows for the upcycling of food waste into printable materials, transforming byproducts such as spent coffee grounds and fruit peels into valuable components for new food items or packaging. This not only reduces waste but also adds value to what would otherwise be discarded (Hassoun, Boukid et al., 2023; Hooi Chuan Wong et al., 2022; Yu & Wong, 2023). Many examples can be found in the literature reporting on the use of 3D printing in food reduction and valorization. For example, in Singapore, where 40% of food imports are lost as food waste, 3D printing can contribute to addressing this issue by converting vegetable wastes into edible diets (Pant et al., 2023). In India, where broken wheat from milling industries and grape pomace are often sent for animal feed or other law-value applications, it was reported that 3D printing can play a pivotal role in valorizing these byproducts in the production of customized foods with improved value (Jagadiswaran et al., 2021).

Food printing technology has gradually advanced from 3D food printing to more sophisticated techniques such as 4D and 5D food printing. 4D food printing introduces the concept of dynamic and responsive food structures that can adapt and change properties when exposed to temperature, moisture, or pressure (Teng et al., 2021). 4D printing, as applied to food, improvises the concept of 3D printing by introducing the element of time. This means that the printed food can transform its shape, texture, or even flavor in response to external stimuli or environmental conditions (Shabir et al., 2024). For example, a 4D printed pasta can change texture and shape when immersed in hot water. Similarly, a 4D printed fruit can ripen and become sweeter over time in response to room temperature. Another aspect of 4D food printing is the potential for incorporating nutritional customization. By using materials that respond to specific stimuli, such as the body's pH levels or temperature, it may be possible to create foods that release nutrients at the precise moment when they are most beneficial to the consumer's health. This level of personalized nutrition could revolutionize the dietary needs and make it easier to meet individual health goals (Ghazal et al., 2023; Koirala et al., 2023; Navaf et al., 2022). To sum up, 4D food printing offers extensive customization, precise, and replicable food production, and significant reductions in food waste by producing items as needed. It enhances nutritional profiles by integrating nutrients directly into the printing process, creating enriched foods. This technology also enables innovative culinary experiences, with foods that change color or flavor over time, and supports sustainability through intelligent materials that reduce the need for extensive storage and transportation (Singh et al., 2024).

4D food printing faces several disadvantages. First, the complexity of achieving controlled responses to external stimuli can lead to inconsistent results, making it challenging to maintain quality and stability in printed food structures. Second, the high costs associated with advanced materials and printing technologies can be prohibitive for widespread adoption. Additionally, the post-processing requirements, such as precise control of temperature and humidity, are energy-intensive and can impact the efficiency and sustainability of the process. Lastly, there are still significant technical hurdles in integrating multi-material printing and ensuring the safety and regulatory compliance of 4D printed foods (Wang et al., 2024).

5D food printing takes food printing concept even further by incorporating additional dimensions that enable the production of the most complex and curved food structures and creation of multisensory food experiences. The creation of interactive textures in 5D printing is achieved using advanced printing techniques and materials. By strategically layering edible materials with varying textures and properties, such as gel-like matrices or microstructures, food items can exhibit dynamic tactile sensations. For example, a printed dessert may feature a combination of smooth, creamy, and crunchy textures within a single bite, offering a heightened tactile experience for the consumer. By varying the textures within a single food item, it becomes possible to cater to individual preferences and create unique flavor profiles. For instance, a 5D printed cake can transition from a smooth and velvety texture to a crispy and airy one during consumption, providing several sensations with each bite. Furthermore, the incorporation of interactive textures in 5D food printing can also offer new opportunities for dietary innovation. By manipulating the physical properties of food, it becomes feasible to create dishes with reduced calorie densities or enhanced satisfaction, contributing to healthier eating habits without compromising on the gustatory experience. This aspect of 5D printing holds significant potential in addressing dietary concerns and promoting wellness through innovative gastronomic solutions (Chen, Teng et al., 2023; Ghazal et al., 2023; Nida et al., 2022; Shabir et al., 2024; Srivastava et al., 2023).

The evolution from 3D to 4D and now 5D food printing signifies a significant shift in food industry. As technology continues to advance, the boundaries of food printing will expand, presenting new opportunities for innovation. The future of food printing has the potential to transform food production and consumption, bringing massive changes to customers' overall experience and interaction with food.

3.6 | From big data to advanced data analytics

Big data has added value to several aspects of the food sector, from precision agriculture to sustainability in the food chain (Figure 7). In precision agriculture, big data analytics are used to collect and analyze vast amounts of data from different data sources such as sensors, IoT devices, drones, satellites, and other sources to optimize agricultural practices. Combined with AI, big data has allowed farmers to adapt to changing environmental conditions (e.g., climate change) effectively by providing insights into crop performance (Bhat & Huang, 2021), soil conditions (Ngo et al., 2023), market demand (Rana et al., 2024), resource allocation (Liu, 2024), and crop yields (Vasudevan & Karthick, 2024).

In dining industry, big data can significantly contribute to reducing food waste by improving forecasting and inventory management. A recent study addressed global food

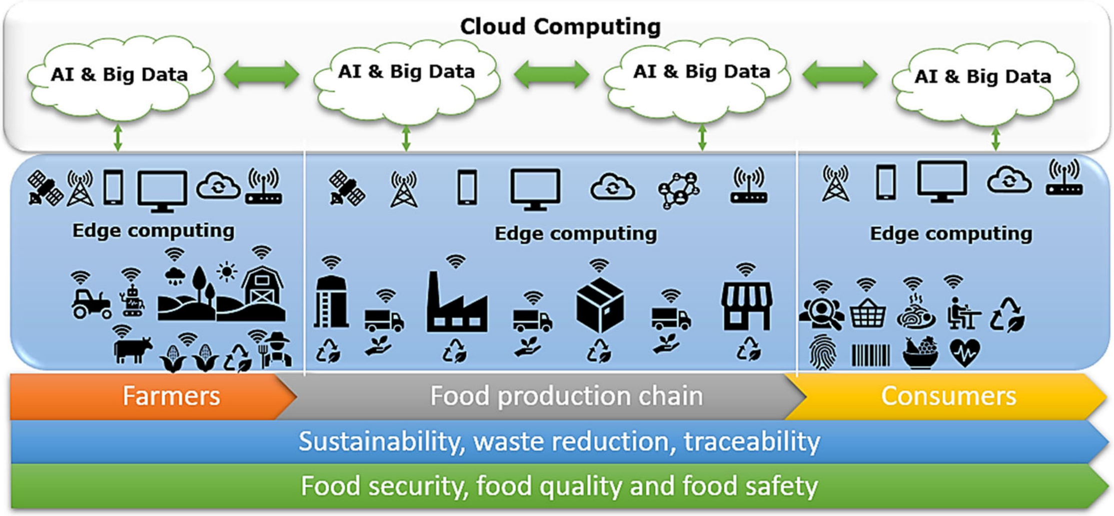


FIGURE 7 From big data to cloud and edge computing from farm to fork.

waste in restaurants by leveraging big data and unsupervised ML to analyze sales data from restaurant tickets (Gómez-Talal et al., 2024). This approach provided insights into customer demand, optimizing product purchases and reducing food waste. By using techniques like multiple correspondence analysis and bootstrap resampling, the study offered a practical tool for restaurant managers to improve forecasting and inventory management, ultimately enhancing sustainability and profitability.

Throughout the food supply chain, big data is used to ensure traceability, minimize waste, and ensure food quality and safety (Ahmadzadeh et al., 2023; Hassoun, Cropotovaet al., 2023; Vasudevan & Karthick, 2024). Food supply chain actors employ AI algorithms and big data for demand forecasting, enhancing inventory management, managing restaurants, and supporting consumers with restaurant selection using mobile-based applications (Chakraborty et al., 2023; Hasan et al., 2024). Moreover, personalized nutrition plans and targeted marketing campaigns arise from analyzing consumer data, while ensuring food safety through real-time monitoring of production processes (Livingstone et al., 2022). Big data can help in adopting sustainability in the food chain by optimizing resource usage and reducing environmental footprint through data-driven decision-making on energy consumption, water usage, and carbon emissions (Cheng & Leong, 2023; El Hathat et al., 2023; Marvin et al., 2022). Although only a few articles have addressed sustainability in the agrifood supply chain, waste management has been the topic that has attracted the most attention (Derakhti et al., 2023).

As big data provides valuable insights into several aspects of the food supply chain, cloud computing emerges as the infrastructure of choice, providing scalable and flexible solutions to manage and analyze these massive datasets (Berisha et al., 2022). It provides services such as data virtualization of resources, data sharing, and data filtering through other systems implemented in the food industries (Rahul et al., 2022). With cloud computing, stakeholders from farm to fork can access real-time information on inventory levels, traceability, transparency, and product quality and safety (Liu, Bouzembrak et al., 2022; Wang, 2023). Food companies can store and access large and diverse amounts of data from various data sources, facilitating data integration and knowledge extraction for better decision-making in areas such as crop monitoring and inventory management (Khan, Hassan, Shahriyar et al., 2023). Moreover, cloud computing accelerates innovation by providing a platform for developers to create and deploy new user-friendly applications in the food sector such as predictive maintenance, demand forecasting, inventory management, waste management, and food chain sustainability (Abbate et al., 2023).

Although cloud computing services help in different ways, they also come with some challenges such as lack of resources, security, managing costs, compliance, governance, managing multiple cloud services, and performance (Marvin et al., 2022; Rahul et al., 2022).

Although cloud computing offers centralized data storage and powerful analytics tools, edge computing brings processing power closer to the data source, enabling real-time insights and autonomous operations at the edge of the network (Iftikhar et al., 2023; Kumar et al., 2023). This is key in environments where immediate responses are critical, such as precision agriculture and quality control (Dedeoglu et al., 2023; Mukherjee et al., 2023). On farm level, sensors and IoT devices collect and process data in real-time, enabling proactive decisions at the field level (Hassoun et al., 2023). For instance, edge-based algorithms monitor crop health (Dhiman et al., 2023), maintain crop quality (Vimalnath et al., 2023), manage animal welfare (Kaur et al., 2023), detect insects (Dhiman et al., 2023), and optimize irrigation schedules, leading to more efficient resource utilization and sustainable farming practices (AlZubi & Galyna, 2023). These advances technologies also enable autonomous agricultural machinery to operate with minimal latency, improving productivity and reducing operational costs (Kumar, Devi et al., 2023; Yu et al., 2023). Edge computing adoption in food supply chains results in a more responsive, efficient, and agile supply chain, leading to improved customer satisfaction. However, the adoption also poses challenges, such as data integration, security concerns, device management, connectivity, and cost (Akbari, 2023).

Industry 5.0 is helping to overcome the current challenges facing big data, cloud computing, and edge computing, transforming the food sector through their integration. Leveraging big data analytics optimizes supply chains by reducing inefficiencies and waste, whereas cloud-based supply chain management systems enhance operational efficiency through real-time tracking and data sharing. Edge computing enables real-time monitoring and quality control in food processing plants, improving food safety by allowing immediate corrective actions. Data virtualization in the cloud improves traceability and compliance with food safety regulations, whereas edge computing enhances productivity through predictive maintenance. These advancements demonstrate how Industry 5.0 technologies are revolutionizing the food sector, making operations more efficient, safer, and cost-effective.

3.7 | From traditional hierarchies to blockchain-based decentralization

Traditional food supply chains suffer from numerous shortcomings, most of which can be attributed to insufficient information or poor data quality. The consequences thereof include a lack of transparency that makes it difficult to track the origin and journey of food products as well as distribution inefficiencies that reduce the level of freshness or even increase contamination incidents and food waste (Kayikci et al., 2022; Magalhães et al., 2021). Fragmented communication and knowledge exchange channels hinder the free flow of information and prevent effective collaboration (Ali & Gurd, 2020). They also make companies more vulnerable to fraudulent activities that could be avoided by using a more secure, immutable, and traceable record-keeping system (Ma, Tse et al., 2022).

These are precisely the problems that solutions based on blockchain technologies can address. Notably, there is not one single blockchain standard, but numerous technologies exist, such as cryptographic techniques and consensus mechanisms (Narayanan & Clark, 2017), which can be combined in numerous ways to address pending organizational problems. For example, in public and permissionless blockchains, anyone can read and validate transactions. In contrast, private and permissioned blockchains restrict participation to selected entities only (Giri & Manohar, 2023). Recently, hybrid solutions have become increasingly popular that combine features from public and private systems (Wang et al., 2023). Importantly, there is no one-size-fits-all solution, and trade-offs need to be made. This is evident in concepts like the "blockchain trilemma"—a trade-off between security, scalability, and decentralization—or the "cap theorem," a classic computer science theorem, which states that the storage of distributed data cannot simultaneously fulfill all three properties of (strong) consistency, availability, and partition tolerance (Zennou et al., 2022).

Despite not being a silver bullet for all current ailments of the industry, blockchain can offer five core enablers for Food Industry 5.0: transparency and traceability, efficiency and cost reduction, sustainability, consumer engagement, and regulatory compliance (Figure 8).

Transparency and Traceability: Blockchain provides an immutable ledger, allowing all participants to verify every transaction within the supply chain. This transparency helps in tracing the origin of food products, from the farm to the consumer, ensuring the authenticity and safety of food items. It effectively combats food fraud and mislabeling, thereby building trust among all partners along the supply chain (Gazzola et al., 2023).

Efficiency and Cost Reduction: Smart contracts automatically execute transactions according to predefined criteria, eliminating the need for intermediaries and reducing transaction costs. Blockchain can significantly reduce manual paperwork, administrative errors, and processing times by automating supply chain processes through such contracts. This streamlines operations, from inventory management to payment processes, leading to significant cost savings (Tayal et al., 2021). For example, a recent study showed that blockchain technology, when integrated with IoT and cloud systems, can significantly enhance the visibility and traceability of the milk supply chain, leading to cost reductions (Vasanthraj et al., 2024). The study found that implementing blockchain in the Australian milk supply chain generates a high return on investment for all stakeholders after 750 cycles. Specifically, the combination of blockchain, IoT, and cloud technologies is more profitable compared to using blockchain alone. For instance, although retailers see benefits after 10 cycles, transporters realize cost benefits after 50 cycles. This integrated approach not only improves data reliability and reduces manual data entry time but also minimizes human

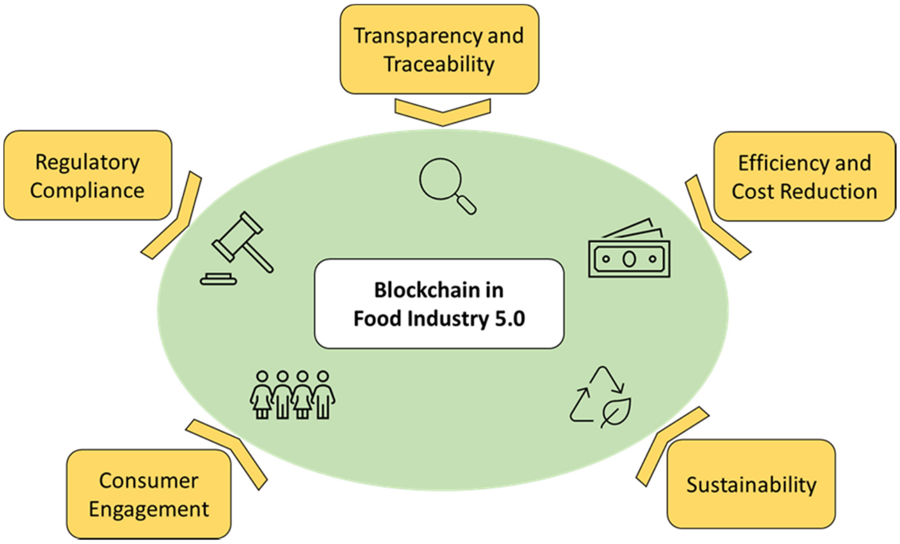


FIGURE 8 Benefits of blockchain in Food Industry 5.0.

costs and response times, ultimately reducing overall supply chain costs.

Sustainability: Blockchain supports sustainable practices by providing verifiable data on the environmental impact, ethical standards, and carbon footprint of food production. It can also meet increasing consumer demand for responsible sourcing and production practices, enabling brands to provide proof of their sustainability claims, and fostering a more sustainable food ecosystem (Giganti et al., 2024; Jan et al., 2023).

Consumer Engagement: Blockchain technology can empower consumers with detailed information about the products they purchase, including origin, ingredients, and sustainability practices (Treiblmaier & Garaus, 2023). This transparency fosters greater consumer trust and loyalty (Treiblmaier & Petrozhitskaya, 2023), as consumers can make informed decisions aligned with their values. With detailed consumer feedback and data collected through blockchain, companies can also innovate and customize products more effectively, aligning with consumer preferences and market trends (Garaus & Treiblmaier, 2021).

Regulatory Compliance: The immutable nature of blockchain records aids in regulatory compliance, allowing companies to efficiently manage and share data with regulators regarding food safety standards, origin, and quality. The technology's nature thus requires novel regulation and innovative approaches when it comes to governance (Krzyzanowski Guerra & Boys, 2022).

In summary, blockchain in Food Industry 5.0 represents a paradigm shift toward a more transparent, efficient, and consumer-centric food supply chain, promoting sustainability and innovation within the global food ecosystem.

3.8 | From augmented reality to metaverse and immersive techniques

Industry 4.0 has paved the way for AR, providing enhanced visualization and real-time data overlays on physical processes, improving precision and efficiency in agriculture and food production. For example, AR in precision agriculture has demonstrated effective solutions with significant impact on monitoring and production, especially when combined with other technologies such as GPS and sensors (Hurst et al., 2021). AR is also proving instrumental in communicating nutritional information and ensuring product traceability, particularly in global markets (Penco et al., 2021).

AR's ability to overlay virtual elements onto real-world environments is having a significant impact on consumer behavior in the food sector. For example, Fritz et al. (2023) showed that AR enhances consumers' mental simulation of food consumption, thereby increasing their desire and likelihood to purchase. Complementarily, Jeganathan and Szymkowiak (2023) reported that AR features, such as simulated physical control and environmental embedding, shape consumers' cognitive and affective responses, indirectly influencing purchase intentions in the context of food delivery. Han, Silva et al. (2022) also explored the possibility to create immersive, impactful, interactive narratives in AR to promote sustainable food consumption.

In retail and marketing, AR is used to improve customer experience and satisfaction. For example, Chiu et al. (2021) highlighted the use of AR in retail food chains, emphasizing its positive impact on customer satisfaction and subsequent marketing strategies. Moreover, Gu et al. (2023) demonstrated the effectiveness of AR in takeaway food packaging, showcasing its ability to improve consumer perceptions and enhance marketing effectiveness. Furthermore, Batat (2021) explored how AR is transforming the restaurant sector and found that, depending on its management, AR has the potential to improve the overall consumer dining experience.

Many other practical benefits of AR can be found in the literature. For instance, a recent study proposed a mobile-based AR structure to assist farmers in measuring and counting Abalone in remote farms (Napier & Lee, 2023). The results showed that the developed tool could achieve a counting accuracy of 95% and significantly decrease the time taken to measure Abalone.

As we move into Industry 5.0, these technologies are evolving toward more integrated and immersive experiences. Virtual reality (VR), for example, immerses the user in a completely virtual environment. VR is being used to develop advanced simulation systems for precision farming, enabling farmers to plan, monitor, and optimize their agricultural practices with unprecedented accuracy. One example is the SimAgri system, a driving simulator for tractors and agricultural machinery that allows precision farming operations to be evaluated and fine-tuned in a controlled virtual environment (Cutini et al., 2023).

VR has also been instrumental in understanding and influencing food-related behaviors. For example, some studies have investigated how the visual quality of food stimuli in a VR environment influences the resulting desire to eat (Ramousse et al., 2023), how the color contrast between food and its background can influence people's food choices in an experimental VR study (Wan et al., 2022), and how VR can be used to study food consumption patterns and eating disorders (Liu et al., 2022; Max et al., 2023). Other studies have explored the validity of VR in replicating sensory experiences. For example, it was reported that visual descriptions were fairly close between real and virtual cookies, highlighting the promising potential of VR for food product development (Gouton et al., 2021). On the contrary, Dawes et al. (2023) found discrepancies in multisensory taste perception between VR and physical reality, indicating the need for further research in this area. VR is also being used to communicate the environmental and health impacts of food choices. For example, virtual supermarkets with interactive pop-ups showing the environmental and health impacts of products have influenced consumers to make greener food choices (Meijers et al., 2022). Applications of VR in education have also been reported in many studies (Gorman et al., 2022). For example, the potential of VR in agricultural education has been explored to create a realistic and immersive simulation of a dairy farm for public education purposes (Nguyen et al., 2024). The outcomes of the study indicated that the developed VR-based dairy farm simulation was regarded as an effective and valuable learning tool. It successfully delivered authentic information to consumers and motivated them to further explore the dairy farm and industry.

Mixed reality (MR), which combines elements of AR and VR, enables the creation of environments where physical and digital objects coexist and interact in real time (Chai et al., 2022). Several studies have focused on the use of MR to improve the ecological validity of sensory and emotional evaluations in food testing. For example, it has been shown that MR can elicit emotional responses similar to real cafes in the context of evaluating tea break snacks, suggesting its utility in obtaining ecologically valid consumer responses (Low, Diako, et al., 2021; Low, Lin, et al., 2021). Long et al. (2023) also emphasized the potential of MR to provide more authentic settings for eating behavior and sensory science research, highlighting the role of this technology in assessing environmental influences on eating behavior. In addition, a number of studies have explored the use of MR to enhance the gastronomic experience. For example, Mesz et al. (2023) examined the emergence of aesthetic emotions in an MR gastronomic experience and found that food enjoyment was significantly correlated with emotions of fascination and enchantment. Similarly, Han, Boerwinkel, et al. (2022) investigated the immersive nature of interactive content narratives developed for MR glasses in a dining environment and found that perceived novelty and curiosity were key to engaging consumers in immersive experiences.

All of the applications examined are only one facet of the broader spectrum of extended reality (XR), which includes AR, VR, and MR. XR refers to all combined real and virtual environments and human-machine interactions (Anastasiou et al., 2023). In this context, Velasco et al. (2021) introduced a model for conceptualizing impossible experiences in mixed and VR, focusing on the context of food. They emphasized the reality-fantasy nature of objects and environments in XR and the extent to which these environments obey or defy physical laws.

Recently, the metaverse has experienced a significant surge in popularity within the internet domain and is swiftly expanding into other sectors. The metaverse offers a unique platform that not only integrates but also surpasses the capabilities of individual technologies such as AR and VR. The metaverse is an interconnected network of ubiquitous virtual worlds that overlay and enrich the physical world. It allows users, represented by avatars, to connect, interact, and experience user-generated content in an immersive and persistent environment (Weinberger, 2022). The metaverse appears to be an important driving force behind the increasing digitalization in the agri-food industry, presenting transformative opportunities and challenges (El Jaouhari et al., 2024). For example, Kang et al. (2023) introduced the concept of the Agricultural

TABLE 1 From augmented reality to metaverse: technologies and their applications in food and agriculture with key studies.

Technology	Description	Applications in food and agriculture	Key studies
Augmented reality (AR)	Enhances visualization and real-time data overlays on physical processes	• Precision agriculture monitoring and production • Nutritional information and traceability • Influencing consumer behavior in the food sector • Enhancing customer experience and satisfaction	Batat (2021), Fritz et al. (2023), Gu et al. (2023), Han et al. (2022), Hurst et al. (2021), Jeganathan and Szymkowiak (2023), Penco et al. (2021)
Virtual reality (VR)	Immerses the user in a fully virtual environment	• Precision farming simulations • Understanding and influencing food-related behavior • Reproducing sensory experiences • Communicating the environmental and health impacts of food choices	Cutini et al. (2023), Dawes et al. (2023), Gouton et al. (2021), Max et al. (2023), Meijers et al. (2022), Qin et al. (2020), Ramousse et al. (2023)
Mixed reality (MR)	Combines elements of AR and VR to create environments where physical and digital objects coexist and interact in real time	• Improving the ecological validity of sensory and emotional evaluations in food testing • Enhancing gastronomic experiences	Han et al. (2022), Long et al. (2023); Low, Diako, et al. (2021), Low, Lin, et al. (2021), Mesz et al. (2023)
Extended reality (XR)	Refers to combined real and virtual environments and human-machine interactions	• Conceptualizing impossible experiences in mixed and virtual reality, focusing on the food context	Velasco et al. (2021)
Metaverse	An interconnected network of virtual worlds that overlay and enrich the physical world	• Optimizing agricultural production chains • Enhancing food marketing and tourism • Advergaming in food	Boccia and Covino (2023), Bonales Daimiel et al. (2022), Kang et al. (2023), Monaco and Sacchi (2023), Ud Din et al. (2023)

Metaverse (AgriVerse), which aims to optimize agricultural production chains for sustainability, highlighting the importance of virtual-real interactions in agriculture-related processes. Ud Din et al. (2023) pointed out that the integration of IoT into metaverse utilities, including agriculture, has led to significant improvements in energy savings, cost efficiency, and operational effectiveness. The authors emphasized the need for continued research in this emerging field to fully harness its potential benefits. In another recent publication, Boccia and Covino (2023) and Monaco and Sacchi (2023) highlighted the potential of the metaverse to revolutionize food marketing and tourism, emphasizing the need for technological investment. In the context of advertising, Bonales Daimiel et al. (2022) underscored the role of the metaverse in advergaming, particularly for food products, pointing out that although potential consumers are generally unaware of advergaming, they do remember brands featured in video games. The following Table 1 summarizes the technologies reviewed, their applications in food and agriculture and the main research studies.

In the food sector, the interaction between Industry 5.0 and the metaverse facilitates a seamless blend of advanced technologies and human-centric approaches. This synergy enhances efficiency, sustainability, and consumer engagement by integrating immersive virtual environments, AR, and AI with traditional agricultural practices. The result is a more resilient and responsive food industry that meets evolving consumer needs and environmental challenges.

3.9 | Advanced cyber-physical systems and digital twins

CPSs are the integration of computation and physical processes, where embedded computers and networks monitor and control physical processes, with feedback loops affecting both computation and physical operations (Lee et al., 2015). In the field of agriculture and food systems, the integration of CPS has led to a number of innovative applications that are transforming practices and improving efficiency. Thus, advances in CPS have had a significant impact on agricultural production and crop management. For example, the use of CPS in precision agriculture, such as in prataculture for precision water regulation

(Ge et al., 2023) and the use of IoT and wireless sensor networks in crop management (Dasig, 2020), exemplifies an increasing trend toward utilizing CPS for more precise and efficient agricultural practices. Furthermore, Jimenez et al. (2020) implemented a cyber-physical intelligent agent for irrigation scheduling in horticultural crops. This precision irrigation system exemplifies the use of CPS to conserve water while maintaining crop health, illustrating a move toward more sustainable agricultural practices.

The integration of CPS in agriculture and food production extends to energy management and environmental sustainability. This includes the integration of renewable energy sources (such as wind energy, solar energy, and wave energy on the sea) through networked micro-grids in fisheries (Chen et al., 2022). Additionally, CPS technology plays a critical role in revolutionizing food supply chains and logistics. For example, Smetana et al. (2021) showed the potential of CPS for increased transparency, efficiency, and personalization in food logistics and supply chain management. These systems enable traceability of food products, ensuring quality and safety from farm to fork. In addition, the incorporation of ML and data analytics can optimize supply chain operations, leading to reduced waste and improved efficiency.

Meanwhile, the concept of Cyber-Physical-Social Systems (CPSS), or socio-CPSs, is gaining ground. CPSS reflects a comprehensive approach that considers not only the technological aspects but also the social and environmental impacts of digitalization in agriculture (Metta et al., 2022). This holistic perspective is crucial to ensure that technological advances are aligned with societal needs and sustainable development goals (Metta et al., 2022; Rijswijk et al., 2021). In this context, Afrin et al. (2022) focused on the use of cloud-enabled robots in a CPSS in the context of agriculture to improve system performance and reduce human effort. The developed mechanism demonstrated a 20% overall improvement in deadline satisfaction, energy consumption, and resource utilization. Kang et al. (2018) demonstrated the application of an agricultural CPSS in the management of traditional solar greenhouses. The system gathers inputs from both social and physical sensors. Social sensors collect data on agricultural product prices in wholesale markets, whereas physical sensors capture essential environmental data within the solar greenhouse. The results showed that the implementation of agricultural CPSS can reduce labor and fertilizer waste, thereby promoting sustainable agricultural production. Hua et al. (2023) described a distributed agricultural service system that integrates ICT for decision support with a focus on improving the productivity and sustainability of smallholder farms. The work proposed a framework of an agricultural CPSS, which consists of information perception, decision support, and decision execution, aimed at monitoring and controlling a solar greenhouse.

Other CPSS studies highlight the socio-ethical considerations in the design of robotics in the digital transformation of agriculture. For example, Eastwood et al. (2022) examined how robotics and automation in pasture-based dairy farming can be developed and implemented responsibly, considering the complex interplay of technological, social, and ethical factors. Similarly, Rijswijk et al. (2021) presented a framework for understanding the interactions among the social, cyber, and physical components of a CPSS in digital dairy farming, with a focus on responsible research and innovation. Other studies explore the implications of big data as part of a CPSS in agriculture (Lioutas & Charatsari, 2020) and the impact of precision agriculture on farmers' social identities (Ogunyiola & Gardezi, 2022). These studies addressed the sustainability challenges posed by big data and the transformation of agricultural practices and farmers' identities due to advanced data-driven technologies.

As a key enabling technology of Industry 5.0, DTs facilitate seamless connectivity between cyberspace and physical space. A DT is a virtual copy or model of a physical entity (the physical twin), which are both interconnected by real-time data exchange (Barata & Kayser, 2024; Singh et al., 2021). Conceptually, a DT reflects the state of its physical twin in real time and vice versa. DTs are increasingly being used in various fields to create detailed virtual models of CPS for improved design, monitoring, and optimization (Kirchhof et al., 2020). A DT can be regarded both as an integral component of CPS and as a standalone technology. Pylianidis et al. (2021), Verdouw et al. (2021), and Cesco et al. (2023) highlighted the central role of DTs in the transformation of smart farming and precision agriculture. These technologies facilitate remote monitoring and management of agricultural operations, improve decision-making through real-time data analysis, optimize resource use, and improve overall farm productivity and sustainability. In particular, some studies demonstrated the use of DTs in detailed soil analysis (Tsakiridis et al., 2023) and structural root architecture modeling (Herrero-Huerta et al., 2021). This technology helps to understand soil properties and root growth patterns that are critical for informed agricultural practices, contributing to effective soil management strategies, improved crop yields, and ecosystem sustainability. In this sense, Purcell et al. (2023) explored the potential of DTs to address challenges related to food security, land degradation, climate change, and population growth, all of which are key issues in sustainable agriculture.

Furthermore, the development of simulators for autonomous agricultural vehicles represents a significant advance in agricultural machinery. The use of DTs in this area enables precision in operations, reduces the need for manual labor, and increases the overall efficiency of agricultural practices (Zhao et al., 2023). DTs can also play a critical role in various applications in both animal husbandry (Zhang et al., 2023) and aquaculture (Ubina et al., 2023). These applications range from modeling the feeding behavior of dairy cows to managing intelligent fish farming systems. In addition, Chen, Zhao et al. (2023), Slob et al. (2023), and Liu, Wang et al. (2023) explored the use of DTs in plant factory and greenhouse management. These applications focus on optimizing plant growth conditions, managing environmental parameters, and improving transplanting processes. In this context, DTs enable precise control of microclimates and plant health, leading to increased efficiency in controlled agricultural environments. Finally, DTs have been used to optimize the supply chain and manage food quality. Defraeye et al. (2021), Shoji et al. (2022), and Dyck et al. (2023) highlighted the importance of maintaining product quality throughout the supply chain, from production to retail, and how DT can improve traceability, reduce waste, and optimize resource use in agricultural logistics. For instance, using DTs for real-time planning, monitoring, and controlling can lead to a 65% utilization improvement for pasteurizers and aging vessels, a 97% utilization for freezers, and 6% reduction in backlog, contributing to more streamlined operations and higher overall efficiency (Maheshwari et al., 2023).

3.10 | Next-generation networks (NGNs) for Food Industry 5.0

With recent technological advancements, we are entering a new phase of industrialization where humans collaborate with advanced technologies like AI, cloud computing, big data, blockchain, and collaborative robots to enhance efficiency, sustainability, and transparency in processes (Maddikunta et al., 2022). Next-generation networks (NGNs); the 6G are expected to bring significant transformations in different verticals, such as food, automotive, and healthcare. In particular, food industry is experiencing a revolutionary phase, propelled by the emergence of innovative technologies, including NGN 6G (Alwis et al., 2021). With expectation of massive advantages, it brings massive opportunities but also significant challenges for all the stakeholders. In this section, we focus on the challenges and opportunities of NGN as a driver of the food industry revolution. We present possible use cases and summarize the impact of NGN on the development of Food Industry 5.0.

Wastage of food, spoilage, and logistic constraints can occur when up-to-date data is unavailable and disjointed procedures are followed. This issue is commonly referred to as inadequacy in supply chain management (Han et al., 2021). Food sustainability can be compromised by conventional techniques that lead to greenhouse gas emissions, soil deterioration, and water shortages (Meier et al., 2015). Due to the vast amount of information available on the Internet, consumers are now more informed and often inquire about manufacturing techniques, the origin of food, and the sustainable practices followed in food preparation before ordering or purchasing (Mazzucchelli et al., 2021). The aforementioned issues pave the way for next-generation communication technology to make a revolutionary impact on the sustainable food industry (Li et al., 2023).

The fifth generation of networks (5G technology) enables rapid data transfer, allowing for real-time analysis of data collected from the food supply chain and its various locations (O'Grady et al., 2019). 5G systems ensure that consumers receive responses with minimal delay, thereby enabling the automation and precise control of a wide range of applications and processes. 5G also incorporates massive machine-type communication, enabling the integration of a large number of devices and sensors. This enhances reliability and creates a seamless environment for connection and data interchange (Sathyanarayana et al., 2022).

One of the prominent applications of 5G in the food industry is supply chain logistics. 5G technology can optimize transportation routes, enable real-time tracking of food products, and automate logistics supply in an end-to-end manner (Apruzzese et al., 2023; Bhat et al., 2021; Dolgui & Ivanov, 2022). When integrated with AI, 5G can facilitate the automation of food processing and manufacturing, as well as enhance monitoring on production lines (Noor-A-Rahim et al., 2022). Furthermore, this integration would aid in anticipating maintenance requirements, ensuring quality control, evaluating processes, and maintaining compliance, thereby enhancing overall operational efficiency.

Wearable devices compliant with 5G technology can assist in monitoring the health of livestock by tracking their location, health, and behavior. These practices enable early detection of illnesses before they spread to other animals, thereby improving the well-being of both the animals and consumers (Devi et al., 2023; Sicari et al., 2020; Tang et al., 2021). Autonomous agricultural equipment can be realized and deployed using 5G-enabled technology. This 5G-powered equipment can be used for remote monitoring, harvesting, and planting activities, thereby enhancing the accuracy and efficiency of the agricultural lifecycle. Similar to wearable sensors in livestock management, 5G-enabled sensors can improve precision agriculture by monitoring weather conditions, nutrient levels, and soil moisture. The resulting analysis can help farmers optimize resources, manage pest control measures, regulate fertilization, and implement targeted irrigation. These practices are expected to lead to better productivity and increased crop yields, especially with the increased use of 5G technology globally. Indeed, by 2025, the share of 5G connections is projected to rise from 8% in 2021 to 25%. Additionally, 5G is anticipated to account for nearly 60% of global mobile service revenue by 2026. The widespread commercialization of 5G will create a solid foundation for the application of smart agricultural IoTs, opening up new opportunities for the agriculture sector (Liu et al., 2023; Majumdar et al., 2024).

Although 5G is facilitating significant progress, 6G has the potential to drive even greater advancements. Offering superior services compared to 5G, 6G is expected to provide advanced communication capabilities for vertical farming and controlled environments. This next-generation network will enable dynamic optimization of robots and subsystems involved in vertical farming, such as temperature regulation, continuous plant health monitoring, and evaluation, thereby ensuring a sustainable and efficient production environment. Additionally, 6G can enhance individual dietary habits by continuously monitoring and analyzing food consumption and daily routines. This technology can offer personalized diet plans and nutrition advice, promoting an optimal healthy lifestyle (Banafaa et al., 2023; Dhinesh & Chavhan, 2022; Polymeni et al., 2023).

Unlike 5G, AI is one of the fundamental building blocks of 6G technology, enabling implicit services for real-time data analysis, predictive maintenance, and decision-making within industrial environments and the food industry (Zeb et al., 2023). 6G offers enhanced network slicing capabilities, allowing for the creation of customized virtual networks tailored to user requirements and the needs of stakeholders in the food industry. Additionally, 6G provides superior communication services with ultra-reliable and low-latency communication, which are ideal for environments requiring a just-in-time approach, ensuring high availability with minimal delays. These features are also crucial for mission-critical applications, such as food delivery through autonomous cars or drones (Alwis et al., 2021; Kumar et al., 2023; Polymeni et al., 2024; Zhang et al., 2022).

The seamless integration of 6G with AI can leverage real-time sensing capabilities from sensors to provide valuable analytical information on demand forecasting, food inventory, food wastage, and the deterioration of perishable items. Although challenges, such as infrastructure development, data security, and talent acquisition, must be addressed, the benefits of 5 and 6G for the food industry are undeniable. As these technologies evolve and become more accessible, their positive impact on food production, consumption, and sustainability will become increasingly evident, shaping the future of Food Industry 5.0.

4 | DISCUSSION, OPPORTUNITIES, AND CHALLENGES

This review aimed to provide insights into the process of transitioning toward a food sector that is more integrated, sustainable, and focused on human well-being. Through the implementation of a comprehensive scoping review encompassing both peer-reviewed and non-peer-reviewed literature within the last 5 years, our objective was to synthesize the fundamental aspects of recent progress and reveal the potential that Industry 5.0 holds for the future agri-food industry. The motivation behind our research was to address the lack of knowledge around Industry 5.0 by providing a detailed vision of the future and identifying enabling technologies that may make these possibilities a reality. During our investigation, we extensively examined a range of advanced technologies, including AI, the IoT, nanosensors, 4D printing, collaborative robots (cobots), and DTs, among others. These advancements serve as the foundational elements of the shift from Industry 4.0, characterized by its emphasis on the integration of technology and the improvement of productivity, to a more advanced Industry 5.0 (Table 2). This evolutionary process is characterized by a comprehensive approach that prioritizes human beings, advocates for sustainability, and enhances resilience. It utilizes technological advancements to promote a balanced cohabitation between humans and machines, reduce environmental impacts, and strengthen our food systems in anticipation of forthcoming obstacles.

The results of our study suggest a notable and progressive transition from the technology-driven and efficiency-focused model of Industry 4.0 to the more inclusive, sustainable, and resilience-focused model of Industry 5.0. This new paradigm emphasizes the significance of creating and applying technologies that not only increase efficiency but also foster environmental sustainability and improve human welfare. Nevertheless, our analysis also reveals that the agri-food sector has just started to explore some aspects related to Industry 5.0, with a significant amount of its capabilities yet to be fully realized. In order to fully exploit the potential of Food Industry 5.0, we propose a comprehensive approach that includes extensive research and development to investigate the practical uses of emerging technologies in the food and agriculture sectors; the creation of supportive policies and regulations that promote innovation while ensuring food safety, privacy, and ethical standards; fostering collaborations across different sectors

TABLE 2 Main Industry 4.0 and 5.0 technologies with their features, use, and limitations.

Technology	Features	Use	Limitations	Industry 4.0/5.0	Key references
Blockchain	Immutable ledger, smart contracts	Transparency, traceability, efficiency, cost reduction, regulatory compliance	High initial implementation costs, energy consumption, regulatory uncertainties	4.0	Gazzola et al. (2023), Giganti et al. (2024), Krzyzanowski Guerra and Boys (2022)
The Internet of Things (IoT)	Network of connected devices	Data collection, monitoring, and control across supply chains	Security vulnerabilities, interoperability issues, data privacy concerns	4.0	Dadhaneeya et al. (2023), Ding et al. (2021), Hassoun (2024b)
IoE (Internet of Everything)	Integration of devices, people, processes, data	Real-time monitoring, logistics optimization, quality control, sustainable production	Complexity in implementation, data privacy issues, high infrastructure costs	5.0	Mohapatra and Rath (2022), Suresh Kumar et al. (2021), Yang et al. (2023)
AI and machine learning	Predictive algorithms, real-time data processing	Crop yield optimization, demand forecasting, precision agriculture, digital marketing	Data availability and quality, high computational costs, need for specialized skills	4.0	Ayoub Shaikh et al. (2022), Houhou and Bocklitz (2021), Yaiprasert and Hidayanto (2023)
Edge computing	Real-time processing, low latency	Precision agriculture, quality control, autonomous machinery	Integration challenges, security concerns, device management	5.0	Dhiman et al. (2023), Kalyani and Collier (2021), Longo et al. (2023)
Big data analytics	Large-scale data analysis, predictive insights	Inventory management, waste reduction, traceability	Data integration, high storage and processing requirements, privacy issues	4.0	Ahmadzadeh et al. (2023), Chakraborty et al. (2023), Sharma, Gahlawat et al. (2021)
Smart sensors	Real-time monitoring, data collection	Soil health monitoring, crop condition tracking, food quality assessment	Calibration and maintenance, data accuracy, cost of deployment	4.0	Liu (2023), Soussi et al. (2024), Turgut et al. (2024)
Miniaturized and nanosensors	Ultra-small sensors for precise measurement	Advanced monitoring of environmental conditions, real-time health tracking	High development and deployment costs, potential ethical concerns	5.0	Grabska et al. (2024), Haris et al. (2023)
Digital twins	Virtual modeling, real-time data exchange	Precision farming, resource optimization, soil management	High implementation cost, data synchronization issues, technical expertise required	5.0	Escribà-Gelonch et al. (2024), Purcell et al. (2023), Tsakiridis et al. (2023)
Cobots (collaborative robots)	Shared workspace with humans, task automation	Food service, food manufacturing, quality inspections	Safety risks, high initial costs, training requirements	5.0	Jacob et al. (2023), Raheem et al. (2024), Romanov et al. (2022)
Recent advances in nanobiotech-nology	Nanomaterials for improved food quality and safety	Enhanced food preservation, nutrient delivery, pathogen detection	Regulatory challenges, potential health risks, high research costs	4.0	Hassoun, Boukid et al. (2023), Lugani et al. (2021), Roy et al. (2022)
Augmented reality, extended reality, and mixed reality	Immersive visualization, interactive simulations	Training, quality inspections, customer engagement	High equipment costs, technical complexity, user adaptation	4.0	Anastasiou et al. (2023), Honee et al. (2022), Lara Penco et al. (2021)
Metaverse	Virtual environments for immersive experiences	Virtual marketplaces, training simulations, customer interactions	High development costs, regulatory concerns, technical barriers	5.0	El Jaouhari et al. (2024), Martínez-Gutiérrez et al. (2024), Tantawi et al. (2024)

to coordinate knowledge, align objectives, and leverage collective capabilities; and strengthening education and training programs to equip the workforce for the ever-changing agri-food industry of the future. In short, our investigation into the prospective path of the food industry reveals an evolution wherein technology assumes a pivotal role in fostering sustainable expansion, enhancing innovation, and cultivating a more profound connection between individuals and the food they consume. Adopting the principles of Industry 5.0 offers a promising opportunity to overcome the most difficult obstacles that the agri-food sector now encounters. This will help create a stronger, more equitable, and sustainable food system. The shift from an Industry 4.0 that prioritized technology and productivity to an Industry 5.0 that encompasses a broader range of fields and dimensions highlights a significant shift toward enhancing the interconnection among food, technology, and society.

Drawing upon the findings presented in this detailed literature review article, the future direction of Food Industry 5.0 is characterized by a deliberate endeavor to adopt more comprehensive, environmentally conscious, and human-centered methodologies. The future vision is supported by the progress and application of technology aimed at improving human capacities, fostering workforce growth, and increasing consumer involvement. This perspective promotes the investigation of potential synergies between humans and machines by employing collaborative robots and immersive technologies that are specifically designed to enhance and supplement human abilities and preferences. The commitment to sustainability and the minimizing of environmental effects is a key driving force behind the forward momentum of Food Industry 5.0. In light of climate change, biodiversity loss, and other urgent global concerns, it is imperative for innovations to give precedence to sustainable methods that enhance the resilience of food systems. This necessitates the implementation of DTs, blockchain, 4D printing, 5G and beyond, and other innovative technologies to enhance the efficient use of resources, reduce inefficiency, and ensure clear and transparent tracking of food from the manufacturing phase to the end consumer.

The resolution of the complex issues confronting the agri-food sector requires a comprehensive strategy that integrates knowledge and skills from several fields, such as biotechnology, nanotechnology, data science, environmental science, and the social sciences. To ensure progress, it is imperative to foster collaborative efforts among academia, business, government, and civil society in order to develop holistic solutions that are both technologically feasible and environmentally sustainable, while also upholding principles of social equity. The prominence of ethical and regulatory considerations becomes evident as we manage the advent of novel technology. It is crucial to establish comprehensive frameworks that regulate the ethical utilization of AI, safeguard data privacy and security, and promote equitable distribution of technical progress in order to ensure that Food Industry 5.0 is in-line with the collective welfare. Furthermore, in order to ensure that the advantages of this new era are available worldwide, including in developing areas and among underprivileged people, it is crucial to make focused endeavors to address digital disparities, facilitate the transfer of technology, and foster inclusive economic development. The necessity of substantial investments in education and training is underscored by the imperative to adequately equip both the present and future workforce to meet the demands of Industry 5.0. These programs should be specifically tailored to provide individuals with the necessary abilities to effectively navigate and exert influence on the ever-changing field of food and agriculture.

Finally, Industry 5.0 presents various safety, security, and challenge considerations. In terms of safety, human-robot collaboration necessitates advanced sensors and AI to ensure safe interactions and prevent accidents, whereas workplace ergonomics must be designed to reduce physical strain and enhance worker comfort. Health monitoring through wearable devices and sensors is also crucial for preventing injuries and detecting health issues early. From a security perspective, robust cybersecurity measures, including encryption, firewalls, and secure communication protocols, are essential to protect sensitive data from cyber threats. Additionally, ensuring compliance with data protection regulations and safeguarding user privacy is vital, especially with the increased use of IoE and AI that collect large amounts of personal and operational data. Blockchain security, although enhancing transparency and traceability, requires strong security measures to protect against potential vulnerabilities and network attacks.

The main challenges of Industry 5.0 include the complex and resource-intensive integration of advanced technologies such as AI, IoE, and DTs into existing systems, necessitating substantial investment in infrastructure and training. Keeping up with evolving regulations and standards related to safety, data privacy, and environmental impact is also challenging for businesses adopting Industry 5.0 technologies. Balancing technological advancement with ethical considerations, such as the fair treatment of workers and responsible use of AI, is crucial, including addressing potential biases in AI systems and ensuring transparent decision-making processes. The high initial cost of implementing Industry 5.0 technologies requires businesses to evaluate the return on investment and manage the financial risks associated with adopting new technologies. There is also a growing need for a workforce skilled in operating and managing advanced systems, making continuous education and training opportunities for employees essential. Finally, achieving sustainability in Industry 5.0 requires ongoing efforts to reduce environmental impact, manage resource use efficiently, and ensure the long-term viability of practices. Addressing these aspects is essential for the successful implementation and sustainability of Industry 5.0 in the food sector and other industries.

5 | CONCLUSION

This comprehensive review is an endeavor to highlight recent research progress on Food Industry 4.0 and identify enabling technologies for future Food Industry 5.0. It is widely admitted that the current Food Industry 4.0 has been profit-centered focusing on increased food productivity and efficiency, which is being enhanced by digitalization and automation. In contrast, future Food Industry 5.0 is predicted to enhance food sustainability, resilience, and human-centricity in the food and agriculture sectors. Food Industry 5.0 can be considered a gradual evolution or incremental improvement of previous technological revolutions that have emerged during the Food Industry 4.0 age rather than sudden, dramatic, and decisive changes, which are the common characteristics of a revolution. Indeed, many of the advancements and technological innovations of Industry 5.0 have been in development for many years and have progressively become more sophisticated and smarter over time.

Rather than introducing entirely new concepts, Food Industry 5.0 seems to build on existing principles, such as enhanced digitalization and increased automation to create more advanced and efficient food production and food processing systems. The development and improvement of these technologies are likely to continue occurring over a long period of time, making Industry 5.0 an evolutionary process rather than a new revolution, at least in the food sector, including agriculture and the food industry. In light of these arguments, it seems legitimate to wonder if Industry 5.0 is just a marketing buzzword or the start of the next industrial revolution. Only the coming few years will tell which scenario plays out.

AUTHOR CONTRIBUTIONS

Abdo Hassoun: Conceptualization; methodology; writing—review and editing; writing—original draft. **Sandeep Jagtap**: Writing—review and editing; writing—original draft; project administration. **Hana Trollman**: Writing—review and editing; writing—original draft. **Guillermo Garcia-Garcia**: Writing—original draft; writing—review and editing. **Linh N. K. Duong**: Writing—original draft. **Prateek Saxena**: Writing—original draft. **Yamine Bouzembrak**: Writing—original draft. **Horst Treiblmaier**: Writing—original draft. **Carlos Parra López**: Writing—original draft; writing—review and editing. **Carmen Carmona-Torres**: Writing—original draft. **Kapal Dev**: Writing—original draft. **David Mhlanga**: Writing—original draft. **Abderrahmane Aït-Kaddour**: Writing—original draft; project administration; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Abderrahmane Aït-Kaddour https://orcid.org/0000-0003-4132-539X

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