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Food processing 4.0: Current and future developments spurred by the fourth industrial revolution

Abdo Hassoun [a,b,*], Sandeep Jagtap [c,**], Hana Trollman [d], Guillermo Garcia-Garcia [e], Nour Alhaj Abdullah [b], Gulden Goksen [f], Farah Bader [g], Fatih Ozogul [h], Francisco J. Barba [i], Janna Cropotova [j], Paulo E.S. Munekata [k,****], José M. Lorenzo [k,l,***]

[a] Univ. Littoral Côte d'Opale, UMRt 1158 BioEcoAgro, USC ANSES, INRAe, Univ. Artois, Univ. Lille, Univ. Picardie Jules Verne, Univ. Liège, Junia, F-62200, Boulogne-sur-Mer, France
[b] Sustainable AgriFoodtech Innovation & Research (SAFIR), Arras, France
[c] Sustainable Manufacturing Systems Centre, School of Aerospace, Transport & Manufacturing, Cranfield University, Cranfield, MK43 0AL, UK
[d] School of Business, University of Leicester, Leicester, LE2 1RQ, UK
[e] Department of Agrifood System Economics, Centre 'Camino de Purchil', Institute of Agricultural and Fisheries Research and Training (IFAPA), P.O. Box 2027, 18080, Granada, Spain
[f] Department of Food Technology, Vocational School of Technical Sciences at Mersin Tarsus Organized Industrial Zone, Tarsus University, 33100, Mersin, Turkey
[g] Saudi Goody Products Marketing Company Ltd., Jeddah, Saudi Arabia
[h] Department of Seafood Processing Technology, Faculty of Fisheries, Cukurova University, Adana, Turkey
[i] Nutrition and Food Science Area, Preventive Medicine and Public Health, Food Science, Toxicology and Forensic Medicine Department, Faculty of Pharmacy, Universitat de València, Avda. Vicent Andrés Estellés, s/n, 46100, Burjassot, València, Spain
[j] Department of Biological Sciences Ålesund, Faculty of Natural Sciences, Norwegian University of Science and Technology, Larsgårdsvegen 4, 6025 Ålesund, Norway
[k] Centro Tecnológico de la Carne de Galicia, rúa Galicia n° 4, Parque Tecnológico de Galicia, San Cibrao das Viñas, 32900, Ourense, Spain
[l] Universidade de Vigo, Área de Tecnoloxía dos Alimentos, Facultade de Ciencias, 32004, Ourense, Spain

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ABSTRACT

"Food processing 4.0" concept denotes processing food in the current digital era by harnessing fourth industrial revolution (called Industry 4.0) technologies to improve quality and safety of processed food products, reduce production costs and time, save energy and resources, as well as diminish food loss and waste. Industry 4.0 technologies have been gaining great attention in recent years, revolutionizing, and transforming many manufacturing industries, including the food processing sector. The aim of this narrative review is to provide an updated overview of recent developments of Industry 4.0 technologies in digital transformation and process automation of the food processing industry. Our literature review shows the key role of robotics, smart sensors, Artificial Intelligence, the Internet of Things, and Big Data as the main enablers of the Food Processing 4.0. advantages in terms of quality control (sorting during processing with robotics and Artificial Intelligence, for instance), safety (connecting sensors and devices with Internet of Things), and production efficiency (forecasting demand with Big Data). However, detailed studies are still necessary to tackle significant challenges and provide deep insights into each of Food Processing 4.0 enablers such as the development of specific effectors for robotics; miniaturization and portability for sensors; standardization of systems and improve data sharing for Big Data; and reduce initial and maintenance costs of these technologies.

* Corresponding author. Sustainable AgriFoodtech Innovation & Research (SAFIR), 62000, Arras, France.
** Corresponding author.
*** Corresponding author. Centro Tecnológico de la Carne de Galicia, rúa Galicia n° 4, Parque Tecnológico de Galicia, San Cibrao das Viñas, 32900, Ourense, Spain.
**** Corresponding author.
E-mail addresses: a.hassoun@saf-ir.com (A. Hassoun), s.z.jagtap@cranfield.ac.uk (S. Jagtap), paulosichetti@ceteca.net (P.E.S. Munekata), jmlorezo@ceteca.net (J.M. Lorenzo).

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1. Introduction

Our planet has been experiencing unprecedented challenges in the last few years, especially the drastic and systemic impact of climate change, in addition to the recent outbreak of pandemics (particularly COVID-19). Meanwhile, the demand for food continues is expected to increase by 56% (62% considering climate change) with the growth of world population, which is expected to reach 9.7 billion people by 2050 (United Nations, 2019; van Dijk et al., 2021). Moreover, the evolution of food processing sector is expected to happen with foods with enhanced nutritional value, consuming fewer resources, preserving biodiversity, and causing low environmental impact (reducing water loss, for instance) in resilient systems to supply this increased demand with complementary programs to prevent food insecurity and hunger (Augustin et al., 2016; Sachs et al., 2019).

Meeting this future demand is considered possible, but important changes are necessary, especially in the area of food processing. This core pillar of our society is expected to evolve and become more sustainable, flexible, resilient, and adaptive (Boyacı-Gündüz et al., 2021; Knorr et al., 2020). Facing these challenges with current food processing systems can be seen as an integrative task due to the complexity of each one of aforementioned challenges and the necessary knowledge to find effective solutions that can be applied in food processing (Augusto, 2020).

This scenario has been motivating professionals of the food industry and researchers to step up and upgrade current processing operations to smarter food processing by incorporating innovative strategies, technologies, and machinery (Jambrak et al., 2021; Kakani et al., 2020). The advances in technology are the necessary breakthrough to strength the developments in food processing towards the solution of current and future challenges. The high connectivity and automation assisted by computing power are key elements that can revolutionize food processing systems (Augusto, 2020).

Essentially, the Fourth Industrial Revolution (or Industry 4.0) aims to increase the interconnection (sensors, devices, machinery, and humans, for instance) and high-level automation to achieve smart processing systems (Hermann et al., 2016; Morella et al., 2021; Oztemel & Gursev, 2020). One of the fundamental aspects of Industry 4.0 is the interdisciplinary that involve a wide set of knowledge related to physical, digital, and biological domains (Chapman et al., 2021; Koh et al., 2020). This combination of characteristics are necessary to facilitate the progression towards more efficient production systems, improve food quality, and reduce food loss (Ghobakhloo, 2018; Onwude et al., 2020; Oztemel & Gursev, 2020; Sadeghi et al., 2022). However, it is important to mention that an universal agreement on the Industry 4.0 components is still lacking (Arslan, et al., 2021; Ghobakhloo, 2018).

In recent years, a clear upward trend has been observed regarding papers published in the field of Industry 4.0 and food processing (Fig. 1). Industry 4.0 encompasses many digital technologies and other advanced solutions (such as Artificial Intelligence (AI), Internet of Things (IoT), robotics, and smart sensors, for instance) that have the potential to accelerate automation and digitalization in industrial sectors, including the food industry.

Recently, a general overview of key Industry 4.0 enablers was given by Hassoun, Aït-kaddour et al. (2022a). However, there is still a lack of comprehensive research on application of Industry 4.0 technologies in food processing. Therefore, the aim of this narrative review is to explore the role of Industry 4.0 enablers in digital transformation and process automation in the processing stage of food industry. Food Processing 4.0 concept will be introduced and the main enabling technologies will be discussed. The role of emerging processing technologies in this context is also discussed. The articles to compose this review were searched on databases Scopus and Web of Science using the terms "Artificial Intelligence", "Big Data", "biosensors", "Internet of Things", "nanosensors", "robotics", "robots", "smart sensors", "emerging processing technologies", "non-thermal processing", and "food industry". The articles published from 2017 to 2022 were selected. Additional relevant studies were manually searched from the reference lists of selected studies and published reviews related to scope of the review.

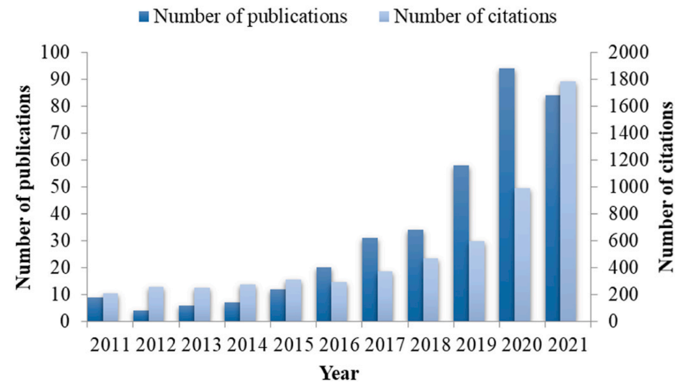

Fig. 1. Number of publications and citations per year on application of Industry 4.0 in the food processing industry over the last decade (search query was performed in May 2022). The following keyword search query was used in Scopus: TITLE-ABS-KEY (Fourth industrial revolution) OR (Industry 4.0) AND (Food processing) OR (Food process).

2. Brief overview of current challenges and main enabling 4.0 industry technologies in food processing

2.1. Current food processing challenges

Food processing entails one or more steps of transformation of raw materials or fresh and inedible agricultural products into edible semi-finished or finished products or food ingredients (Bhargava et al., 2021a; McClements & Grossmann, 2021; Pérez-Santaescolastica et al., 2021; Qian et al., 2022; Teng et al., 2021). Food processing enables the production of a wide variety of food products that are convenient and affordable for consumers, hence the increased demand for processed foods in contemporary society (Ndisya et al., 2021; Qian et al., 2022). However, food processing has complex challenges that were introduced and gradually evolved with the industrial revolutions and emerging challenges that are still yet under investigation and at initial phases of incorporation into the industry after the mechanization of food processing: food safety, competitiveness, plant-based foods, quality control, and food security (Augusto, 2020; Silva et al., 2018).

Food safety is a constant concern about food processing due to the food borne outbreaks registered every years across different food categories. One of the main recurrent causative agents of food borne outbreaks are contamination with pathogenic microorganisms (such as *Campylobacter* spp. and *Salmonella* spp.). Consequently, regular updates in governmental pages (Centers for Disease Control and Prevention, 2022) and annual reports (European Food Safety Authority, 2021) provide a comprehensive view of latest cases and trends. The contamination with toxic substances from vast sources (sanitizers, mycotoxins, pesticides, environmental pollutants) are also routinely observed in food recalls (FDA, 2021b).

The competitiveness of food market became a key characteristic after the modernization of food industry in the post-World War II period. Foods were viewed and perceived by consumers as goods with characteristics beyond their basic function (source of vital nutrients) and the presence of many companies sharing the same market favored the necessity of differentiation in the face of the competition (Silva et al., 2018). Consequently, two key research fields flourished from this scenario: sensory analysis and consumer science. The expansion of knowledge derived from the advances in these two areas generated new knowledge and expanded the view, technologies, concepts of food processing and open the possibility to have a better alignment of consumers preferences and desires with food processing (Fiorentini et al., 2020).

One key current example are the advances in the production of plant-based foods (intended to compete with animal protein foods such as meat, milk, dairy and meat products) due to environmental and health concerns associated with their production and consumption (Wickramasinghe et al., 2021). Due to the wide consumer interest in the consumption of this new category of processed foods, many products were developed and are on the supermarkets (Curtain & Grafenauer, 2019). However, advances in this food category are still necessary to obtain products with higher acceptance in terms of colour, flavor, and mouthfeel, and the appropriate nutritional information (Fiorentini et al., 2020; Wickramasinghe et al., 2021).

Quality control during processing is a necessary activity to monitor food characteristics and processing conditions and check their compliance with defined criteria (Ali & Hashim, 2021). However, the continuous monitoring of food characteristics and processing in modern production lines has important limitations. The fundamental organization of activities is comprised by acquiring representative samples, sample preparation, formal analysis, and interpretation of results. These activities are currently performed using protocols that require laboratory infrastructure, equipment, trained and skilled technicians, constant expanses with reagents and solvents, and long periods (several hours or days) until conclusive results, which support the study and further implementation of more sophisticated systems to improve the management of quality control (Di Rosa et al., 2017).

Food adulteration (a core aspect of Food Security) is a serious dishonest activity punished by law that is usually performed to generate additional profit (estimated to generate a global cost between 10 and 40 billion dollars/year) and deceive consumers at the expense of food quality (low nutritional and not compliant raw materials, for instance) and safety (unknown or unverified origin) (FDA, 2021a; Munekata et al., 2020). Cases of food fraud occur across different food production systems involving mainly fats and oils; seafood; meat and meat products; honey and royal jelly; dietetic foods, food supplements, fortified foods; fruits and vegetables; and infant formula (European Commission, 2022; FDA, 2021a). Another form of altering food is known as food tampering, which consist in the intentional inclusion of compounds or materials to cause harm to consumers and promote a food borne outbreak (FDA, 2018). Although rare, food tampering has also been monitored in recent reports (European Commission, 2020).

Once fraudulent actions are disclosed, one of the effects is the reduction of perceived confidence and trust from consumers in the involved food product and brand/company. Moreover, this effect seems to be extended to corresponding regulatory agencies and the productive sector as a whole (Kendall et al., 2019). Efforts to face the complexity of food fraud, especially with the imposed restrictions and challenges from COVID 19 pandemic, require coordinated actions and implementation of solutions (such as digital technologies) to improve the compliance with regulatory monitoring and discourage fraudsters to take advantage of consumers in circumstances of supply chain gaps (characterized by panic-buying and stockpiling) (Onyeaka et al., 2022). In this sense, increasing transparence, accessibility, security, and immutability of data registered from food production can potentially reduce food fraud (Antonucci et al., 2019).

2.2. Key 4.0 industry technologies and technological adoption in food processing

A historical overview of the industrial revolutions indicate that key transformations were progressively changing the food production lines

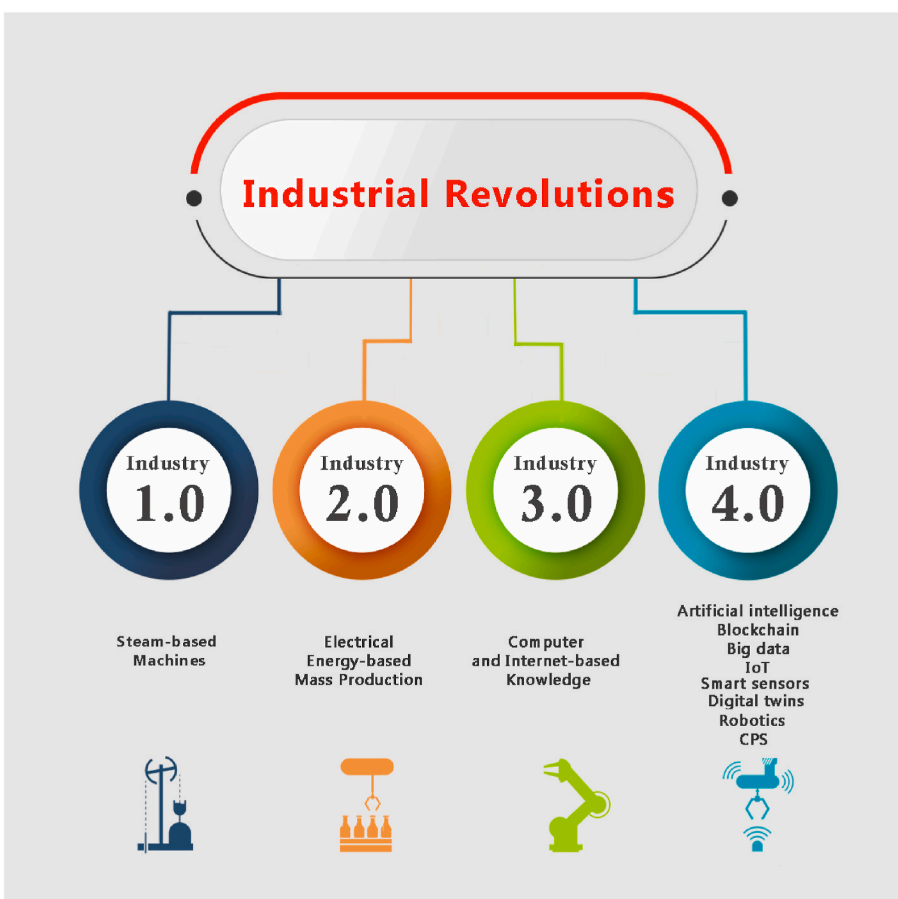

Fig. 2. The four industrial revolutions and the main enabling technologies.

(Fig. 2). The first industrial revolution (occurred late 18th century) enable the use of steam engine to carry out repetitive tasks in food production and the developments of steam-based tasks, specifically thermal processing (pasteurization and sterilization). In terms of mechanization, the milling of grains was upgraded from human-, animal-, wind-, or water-powered systems to a steam-powered machinery during the 18th century (Westworth, 1932). However, one of the key development for food processing using steam occurred much later. The formalization of pasteurization as technique is attributed to Louis Pasteur around years 1860's (supported by his studies to prove the role of microorganisms in food spoilage) and it was only in 1876 when he and Charles Chamberland developed the first autoclave (Misra et al., 2017).

The second industrial revolution (late 19th century) led to the utilization of electricity in food production. Steam-powered food processing equipment were gradually replaced by electric-powered counterparts and new equipment were also introduced. An intense development of machinery specific to food processing was derived from this period such as juice extraction machine by Norman Walker around 1930 (Omoregie et al., 2018), vacuum packaging systems by Karl Busch around 1960 (Patil et al., 2020), and the initial upgrade from batch to continuous pasteurizing systems (Rankin et al., 2017).

One key development from this period was the creation of refrigeration systems. Key events for lowering temperature in food production include the increasing necessity for cold storage and transportation of ice and foods during the 19th century and the eventual use of refrigeration for meat processing and preservation at the end of that century (Misra et al., 2017). The advances in electric systems and studies with gases to cool foods (initiated during the first industrial revolution) enable the development of electric-refrigeration systems to replace natural ice by mechanically produced ice at the end of 19th century (Sandvik, 2017).

The third industrial revolution (during the 1970s) inserted the digitalization of processes with the development of microchips, which paved the way for the improved control of food processing lines (Teixeira & Shoemaker, 1989). Continuous and more comprehensive processing with computers (with programmable and automated characteristics) and new equipment became possible (Goff & Griffiths, 2006). One main technology developed during this period is the development of extrusion as one-step process and the development of texturized plant protein products (especially texturized soy protein) (Riaz, 2000). The initial insertion of robotics in food processing (around 1990) happened during this revolution (Nayik et al., 2015). Additionally, the third revolution is also marked by the advances leading to the development of irradiation (ionizing and microwave systems) systems for microbial decontamination of herb and spices (Farkas & Mohácsi-Farkas, 2011).

The great technological innovations and rapid developments that occurred in recent years have led to the emergence of Industry 4.0, with automation and interconnectivity being the main features (Morella et al., 2021; Oztemel & Gursev, 2020). Industry 4.0 is an interdisciplinary topic, involving a wide set of knowledge related to physical, digital, and biological domains (Chapman et al., 2021; Koh et al., 2020). Industry 4.0 has been characterized by smart systems and more intelligent manufacturing and production processes due to the development of advanced technologies at all stages of the supply chain, increasing efficiency and food quality and reducing food loss (Ghobakhloo, 2018; Onwude et al., 2020; Oztemel & Gursev, 2020; Sadeghi et al., 2022). Robotics, smart sensors, AI, IoT, and BD play an important role in the food processing (Hassoun, Aït-kaddour, et al., 2022; 2022b). Additionally, Industry 4.0 main enablers include smart sensors and the IoT (Javaid et al., 2021; Ullo & Sinha, 2021; Zhang et al., 2022), robotics (Bader & Rahimifard, 2020; Dzedzickis et al., 2022; Iqbal et al., 2017), AI (Kakani et al., 2020; Ramirez-Asis et al., 2022; Sun et al., 2019), and Big Data (BD) (Jin et al., 2020; Tao et al., 2021) have been recently reviewed.

Robotics and automation are among the main Industry 4.0 enablers that provide many opportunities to perform multiple operations in various industrial sectors, including the food processing industry. While the first developed autonomous robots were intended to perform simple repetitive jobs (as important invention from the third industrial revolution), recent technological advances have enabled the design of more advanced robots that are able to perform high-level tasks and difficult operations, leading to increased productivity and decreased labour and manufacturing time and cost (Bader & Rahimifard, 2020; Chen & Yu, 2022; Iqbal et al., 2017; Jagtap, Bader, et al., 2021). The use of robots has become more popular in recent years, especially during the COVID-19 pandemic to meet the growing demand for automation and robotic systems in the food sector, which is reflected by the increased number of studies published during the last two years (Fig. 3a). Robots are often combined with sensors and other Industry 4.0 elements.

Smart sensors are an important Industry 4.0 technology that plays a significant role in data acquisition and process automation. The development of sensors, initially, as mechanical systems with limited capacity to sense and return information (Moncrieff, 1961) evolved to portable and computer-controlled instruments (Qian et al., 2021). Sensors are being increasingly developed and implemented in various stages of processing lines to improve the control in food processing. Consequently, the management of quality control can be improved to reduce the loss of food quality and production cost (Franceschelli et al., 2021; Jambrak et al., 2021; Javaid et al., 2021). In recent years, the number of publications reporting advances with the application of smart sensors (or nanosensors/biosensors) in the food industry has increased significantly (Fig. 3b), especially with the recent advances in nanotechnology and biotechnology that have accelerated the development of miniaturized sensors (Chen & Yu, 2022; Fernandez et al., 2022; McVey et al., 2021; Ren et al., 2022).

AI is one of the emerging digital technologies that has received great attention in recent years, being a creative tool that simulates the human reasoning ability and intelligence using computers, robots, and digital equipment (Ben Ayed & Hanana, 2021; Misra et al., 2020). AI has progressed from its key concepts of machine intelligence (Turing Test), computer development, and the creation of information theory to the development of modern learning/training strategies for complex computing systems (Haenlein & Kaplan, 2019). The role of AI in the food industry is becoming increasingly important, due to its ability to work and react like humans to perform many tasks quickly and in real-time (e.g., cleaning and ensuring hygiene standards, preparing food and drink, detecting potential risks during food production, and sorting food according to its quality), supporting the implementation of smart factory (Bai et al., 2020; Di Vaio et al., 2020; Jambrak et al., 2021; Ramirez-Asis et al., 2022). Therefore, the research on potential application of AI in the food industry has witnessed an increasing interest in recent years (Fig. 3c).

Another key 4.0 technology is **IoT** that can be defined as a network of "things" that can be located, identified, and operated upon, and which are connected through sensors (Ng & Wakenshaw, 2017). This technology has the potential to turn ordinary sensors into intelligent sensors and promote remote sensing (Javaid et al., 2021; Ullo & Sinha, 2021). The history of IoT is recent due to its first definition in 1999 and characterized by the intensification in the communication between "things" and developments aligned with mobile internet (Tzafestas, 2018). The benefits of application of IoT in food processing are numerous, including the improved food safety, increased efficiency, enhanced production and transparency, and optimized food production systems (Astill et al., 2019; Jagtap, Duong, et al., 2021). There has been an increasing interest in using **IoT** technologies in the food industry, which has been intensified after the year 2016, as can be noticed from Fig. 3d.

In modern food industry sectors, large and heterogeneous data, referred to as Big Data (**BD**), are produced from various operations during food processing. The advances in BD have been characterized by the combination of key elements (5Vs) to deal with current data generation: volume, variety, velocity, veracity, and value. The progression

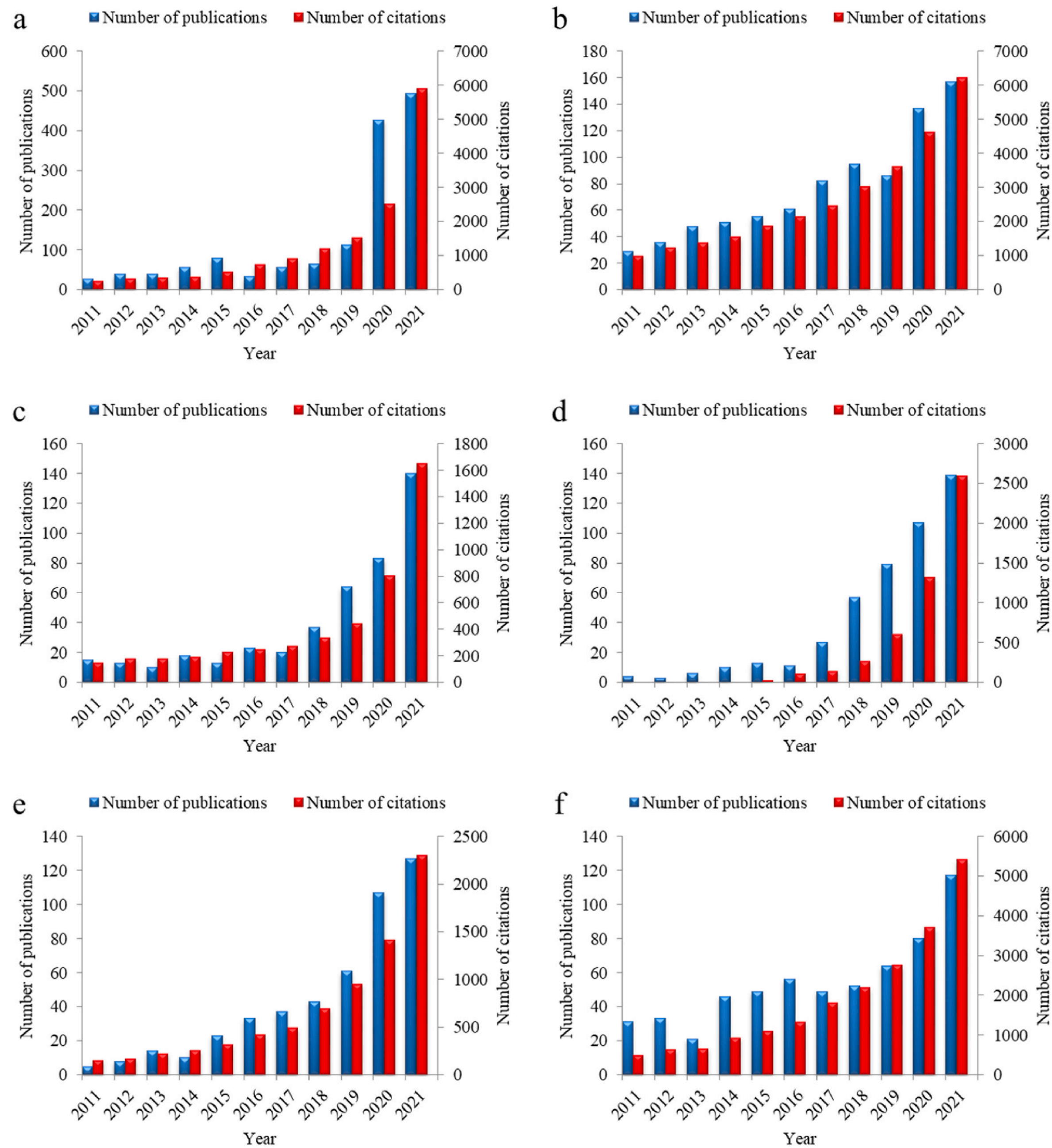

Fig. 3. Number of publications and citations reporting on the application of robotics (a), smart sensors (b), Artificial Intelligence (c), The Internet of Things (d), Big Data (e), and emerging technologies (f) in the food industry during the last decade (search query was performed in May 2022). The following keywords search query were used in Scopus: (a) TITLE-ABS-KEY (Robotics) OR (Robots) AND (Food industry), (b) TITLE-ABS-KEY (Smart sensors) OR (Nanosensors), OR (Biosensors) AND (Food industry), (c) TITLE-ABS-KEY (Artificial Intelligence) AND (Food industry), (d) TITLE-ABS-KEY (Internet of Things) OR (IoT) AND (Food industry), (e) TITLE-ABS-KEY (Big Data) AND (Food industry), and (f) TITLE-ABS-KEY (Emerging processing technologies) OR (Nonthermal processing) AND (Food industry) (f).

from times when management of information and data were considered painstaking, complex, and time consuming tasks (population census prior to World War I, for instance) to modern management of data assisted by computers that quickly and accurately process digital data streams in any form (structure, semi-structured, and non-structured) demonstrates the importance of this technology (Barnes, 2013; Batistič & van der Laken, 2019; Johnson et al., 2017). As for the other Industry 4.0 technologies, the research interest in BD has been increasing in the last decade (Fig. 3e) due to its many advantages offered (Astill et al., 2019; Tzounis et al., 2017). BD can be used to align food processing with strategies to reduce food loss and food waste (Mishra et al., 2017), enhance demand forecasting (Alicke et al., 2016), increase process optimization and improve new product development (Jagtap & Duong, 2019; Tzounis et al., 2017), and address concerns of food safety (Jin et al., 2020).

3. Food processing 4.0 concept

Industry 4.0 technologies, such as AI, IoT, BD, robotics, smart sensors, blockchain, and augmented reality, among others, have been widely investigated in many research and industrial application areas in recent years. In the food industry, the application of these technologies (termed Food Industry 4.0, or simply Food 4.0) has offered many advantages to food quality, safety, traceability, and sustainability. In the current work, we introduce the concept of Food Processing 4.0 to explore how exploiting these technologies in the best possible way will benefit the food processing sector. Food Processing 4.0 concept refers to processing food in the current modern digital era by harnessing Industry 4.0 technologies to improve food quality and safety of food products along with reducing food processing costs and time, saving energy and resources, and reducing food loss and food waste. In this work, robotics, smart sensors, AI, IoT, BD are considered among the main enablers in the food processing sector (Fig. 4), although other Industry 4.0 technologies (such as blockchain, 3D printing, cloud technologies, and cyber-physical systems) can be also applied but to a lesser extent (Hassoun, Aït-kaddour, et al., 2022; 2022b).

4. Industry 4.0 in food processing

4.1. Use of robotics in food processing

The need for more automation and robotics has been dramatically established over the last two years with the outbreak of the COVID-19 pandemic, due to labour shortages and movement restrictions of workers needed in food processing worksites and the other unprecedented disruptions caused by this pandemic, e.g., high degree of sanitation and reduced human contact. These circumstances have opened new opportunities for robots to take over since many studies have reported that robotics can contribute to addressing many challenges posed by the COVID-19 (Aday & Aday, 2020; Dzedzickis et al., 2022; Wang et al., 2022).

As defined by the International Standards Organization (ISO), robots are autonomously controlled, reconfigurable, and reprogrammable machines that offer multiple degrees of freedom. Robots can be either stationary or mobile and are designed for use in several applications, which typically aim to replace manual labour. Robots are programmed to mimic humans and their actions, making them dexterous, and thus more flexible than regular automated machinery. These robots comprise of the robot itself, an arm, the wrist, and an end-effector (such as a hand) that performs the tasks (Dzedzickis et al., 2022; Sandey et al., 2017).

In food processing, they are mostly used for pick and place operations, to complete tasks such as sorting, packing, and packaging (Bader & Rahimifard, 2018; Jagtap, Bader, et al., 2021; Wang et al., 2022). Robotic automation is most efficient when implemented to resolve or improve certain manufacturing and processing scenarios. These include production line bottlenecks, hazardous or unfavourable manufacturing environments, simple and repetitive processes, which can be tedious for human labour, and facilities with a highly variable product line, which requires frequent changeovers (Bader & Rahimifard, 2018; Dzedzickis et al., 2022; Sandey et al., 2017).

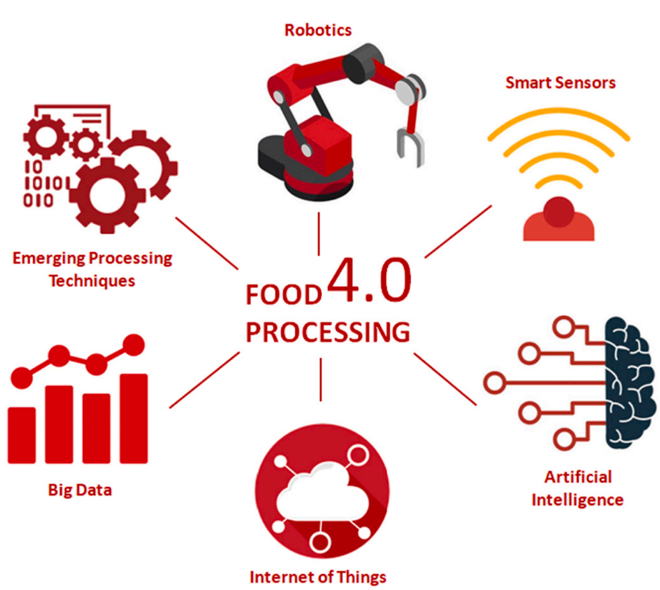

Fig. 4. Food Processing 4.0 elements.

Robotic automation offers food and beverages manufacturing many benefits, the main and most vital one being flexibility. Essentially, robotics provides reconfigurability and quick adaptation into new work environments and new processes. All while ensuring products are high in quality and uniformity, as robotics follow set planned actions repeatedly in a precise manner. Moreover, there is less workforce injury due to repetitive movement, thus improving overall working environment. Increased efficiency ensured production cost and time is reduced, and that waste material is kept at a minimum. All of these benefits ensure the company maintains a competitive advantage against others (Bader & Rahimifard, 2018, 2020; Chen & Yu, 2022; Schwarz & Wydra, 2021).

Despite the onset of Industry 4.0 and the technological advancements of robotics for food processing applications, their implementation rates is currently low due to specific challenges to be tackled for its wide use in the food industry (Bader & Rahimifard, 2020; Duong et al., 2020). The first and most challenging aspect is related to the essence of foodstuffs, which are naturally soft, fragile and can often have slippery surfaces. Moreover, many foods are non-rigid, thus making them more prone to damage under pressure. Specially designed end effectors are being needed and developed to overcome this challenge. Seven types of end effectors are currently available for use with food applications. These gripper mechanisms include pinching, enclosing, pinning, pneumatic, freezing, levitating, and scooping mechanisms (Bader & Rahimifard, 2020). Other challenges encompass strict hygiene requirements demanded by the food industry to ensure the food is safe for consumption, as well as the economic barriers related to the current high costs associated with purchasing and maintaining robotics (Wang et al., 2022).

4.2. Use of smart sensors in food processing

Various types of sensors have been developed and used to make real-time monitoring and measurements along the food processing lines (Hassoun, Aït-kaddour, et al., 2022; Jambrak et al., 2021). Nowadays, a wide range of sensors are available to monitor the quality and safety of food through the measurement of humidity, temperature, variations in gas concentrations (such as oxygen and carbon dioxide), and changes in pH (Amin et al., 2022). Smart sensors can be classified as physical sensors, chemical sensors, and biological sensors. Smart sensors can be also divided into several groups according to the measured analytes; biological and chemical contaminants, allergens, nutritional ingredients, and food additives (Cheng et al., 2022; Oveissi et al., 2022; Zhang et al., 2022).

For example, a light scattering sensor was developed to detect three major foodborne pathogens, *S. enterica*, STEC including *E. coli* O157:H7, and *L. monocytogenes* in food (Abdelhaseib et al., 2019). This non-invasive sensor achieved high classification accuracies (ranging between 84 and 100%), which could lead to a significant saving in terms of time and cost compared to traditional methods. In another study, a biosensor was synthesized for the detection of milk protein allergens in food processing environments, achieving detection limits superior to existent traditional methods (Ashley et al., 2018).

Smart sensors based on spectroscopy are being developed and employed in various food sectors, including monitoring food processing operations and determining food quality (McVey et al., 2021). Especially the use of optical sensors based on hyperspectral imaging (HSI) has become popular in recent years due to the many desirable features of this technology. For example HSI technique operating in the spectral range 400–1700 nm was used to assess quality changes in purple-speckled cocoyam slices during hot-air drying processes (Ndisya et al., 2021). Prediction models were successfully built using few wavelengths, enabling to predict several quality parameters with excellent performance.

One of the emerging trends in sensors is their use in active and intelligent food packaging. Integration of sensors into packaging has the potential to improve food quality and safety and extend the shelf life in addition to communicating information to users about the changes in the product and environment, product history, and authenticity (Cheng et al., 2022; Gökşen et al., 2022; Firouz et al., 2021; Yousefi et al., 2019). For example the application of red cabbage anthocyanins in smart bio-based food packaging and biosensors was recently discussed in details by (Abedi-Firoozjah et al., 2022).

Electronic sensors, such as electronic nose (E-nose) and tongue (E-tongue) are being developed and used in different food-related applications, including food processing. E-nose simulates the human nose to detect and identify volatile organic compounds, distinguishing complex odours with an array of sensors. E-nose has also been effectively implemented in food spoilage detection, meat and fish freshness evaluation, shelf-life prediction, classification and discrimination, as well as adulteration (Chitrakar et al., 2021; Mohd Ali et al., 2020; Shi et al., 2018). Recently, E-nose combined with artificial neural network (ANN) was used to explore the relationship between different brewing processes and quality of vinegar (Li et al., 2022). The types of vinegar in different brewing processes were better distinguished, with correct classification rates of 98.6% and 96.7% for training and prediction, respectively, based on ANN modelling compared to physicochemical traditional parameters. Another important smart sensor is E-tongue that simulates the human tongue to perceive the five basic tastes (i.e., sweetness, acidity, bitterness, salinity, and umami), based on electrochemical reactions, such as voltammetry, potentiometry, and conductometry (Chitrakar et al., 2021; Tan & Xu, 2020; Zhang et al., 2022). The application of E-tongues in different food processing lines, such as fruits and vegetables, milk and milk products, fermented beverages, juices, among others, was reviewed by Wadehra & Patil (2016).

In recent years, miniaturization and portability have become important trends due to rapid technological advances in many scientific fields, particularly in biotechnology and nanotechnology (Chen & Yu, 2022; Rodriguez-Saona et al., 2020). For example, the development of user-friendly smartphone-based biosensors has been accelerated due to the increasing advances in smartphone technology (Amani et al., 2022; Roda et al., 2016; Yousefi et al., 2019).

4.3. Applications of AI in food processing

The use of AI in food processing industry is expected to have a compound annual growth rate (CAGR) of 45% between 2021 and 2026 (Mordor Intelligence, 2022). The main applications of AI in food processing include food sorting, quality control and safety compliance, maintenance, and optimizing production (Nayak et al., 2020). AI offers many possibilities to optimize and automate processes, cut costs, and reduce human error.

Food sorting: The most significant use of AI in food processing is in the sorting of food and products. Historically, the sorting processes have required considerable human labour that was monotonous and repetitive. AI connected to imaging technology uses algorithms to analyse various aspects of food and identify deficiencies. Sensors may examine colour, biological characteristics, and shape (length, width, and diameter, for instance). An example is the food sorters and peelers developed by TOMRA that demonstrated not only generous processing capacity, but increased food quality and safety (Kumar et al., 2021). Similarly, Kewpie Corporation in Japan has created an AI-based TensorFlow machine that can identify anomalies in food coming from farms (Kumar et al., 2021).

Food safety and quality: Establishing traceability systems for the safety and quality of processed foods is a challenge due to the variety of raw materials, batch mixing and resource transformation. As such, statistical models are an important part of food processing (Qian et al., 2022). Traceability during food processing may be improved with AI employed for processing flow analysis, batch mixing simulations, and batch optimization modelling.

Artificial biomimetic technology (E-noses, E-tongue, and computer vision) are intelligent methods based on changes in smell, taste and appearance. Chemical sensors can accurately distinguish various food odours supported by an AI algorithm with access to a database of potentially dangerous odours. In a food-processing environment, E-noses could assist with the detection of contaminants. For instance, an E-nose coupled with chemometric techniques may be a reliable instrument for monitoring food drying processes (Sun et al., 2019).

Computer vision can also reveal nutritional information of food (Kakani et al., 2020). One application is the detection of pesticide residue in berries to measure the measure the effectiveness of washing step during their processing (Wang et al., 2021). Imaging and sensing devices can also be used to identify food residue on equipment that has the potential to contaminate an entire product line. Self-Optimizing-Clean-In-Place (SOCIP) uses ultrasonic sensing and optical fluorescence imaging to detect the presence of food residues and microorganisms inside food processing equipment (Simeone et al., 2016). AI can also ensure employees have appropriate personal protective equipment, do temperature checks, and grade food cleanliness. Surveillance systems can detect and track people as well as their movements and attire. Face- and object-recognition can identify if masks or hair coverings are being worn (Kumar et al., 2021).

Maintenance: AI can optimize technical parameters for higher output and greater reliability and technical availability of equipment using predictive maintenance, e.g., in wheat grain processing (Massaro et al., 2020). The ability to accurately determine time-to-repair and cost-to-repair is possible with AI via data categorization and the delivery of predictive alerts. Condition monitoring can determine the real-time state of equipment for improved effectiveness. Fixed maintenance intervals can be partially replaced with data-based predictions obtained from sensors. Predictive algorithms can identify issues in advance of serious complications requiring production to cease. Different types of maintenance that AI may play a role in are shown in Table 1.

Optimizing production: AI may be connected with other technologies such as IoT, remote sensing, BD analytics, machine learning, and

Table 1
Optimizing maintenance systems and processes supported by AI (adapted from Uptake, (2018)).

	Total Productive Maintenance (TPM)	Planned Preventive Maintenance (PPM) or Planned Maintenance (PM)	Predictive Maintenance
Description	A holistic system resulting in fewer breakdowns, less downtime, increased production and improved safety	A part of TPM that is scheduled by time or events necessitating repairs	Uses high-frequency raw data readings, machine learning, historical performance data and contextual data to draw attention to condition-based maintenance needs
Data Used	Historical maintenance data for lower repair budgets	Historical maintenance data for lower repair budgets	Historical maintenance data, sensor data and contextual information like weather and geographic data for real-time, condition-based alerts
The role of AI	Enables Autonomous Maintenance: equipment maintenance is carried out by the machine operators	Helps businesses aggregate and interpret data faster	Interprets large amounts of data into meaningful intelligence and actionable insights possibly using edge computing

blockchain to develop synergistic approaches to optimize advanced thermal and non-thermal processing technologies (Jambrak et al., 2021). AI can enable real-time monitoring instead of waiting for the end of a production cycle to identify issues. Optimizing resource consumption (e.g., energy and water) can immediately reduce production costs (Funes et al., 2015). Significant performance improvements can be achieved while reducing overall total cost and the need for continuous operator oversight (Lockey & Bhartia, 2019).

Examples of process optimization include a cheese manufacturer that used correlation models trained on historical data of 29 different processing variables to classify impacts on the final product moisture content. The result was a reliable increase of average moisture content within regulatory compliance limits, resulting in significant savings (Ziynet Boz, 2021). Likewise, an AI approach using unstructured and correlated data for the analysis and management of processes has also been employed with bacterial spoilage indicator data from 23 dairy processing facilities to identify post-pasteurization contamination factors (Murphy et al., 2021).

4.4. Applications of IoT in food processing

There is a wide range of industrial applications of IoT, and as such IoT is developing rapidly and receiving increasing attention. Indeed, the IoT market is expected to reach $1.1 trillion in revenue by 2024 (GlobalData, 2021). The main advantages that IoT provides are related to monitoring processes and products. The large amounts of data collected by IoT systems can support decision making in industry.

IoT architecture is generally formed of 3–5 layers, depending on the classification used (see examples in Fig. 5). These layers may include, for instance, sensing, networking, service and interface layers (Xu et al., 2014). Under this classification, the sensing layer contains the hardware, the networking layer permits data transfer, the service layer creates and manages services, and the interface layer allows interaction by users and other applications.

IoT has a lot of potential to improve operational performance in food supply chains. With this aim, Jagtap, Garcia-Garcia, and Rahimifard (2021) developed a framework to improve the resource efficiency of food manufacturing through the design and implementation of IoT-based tools. Such framework supports decision making for reduction of food waste generation and energy and water consumption. However, other food operations can also improve their transparency, traceability, monitoring, security, control, and overall sustainability performance via IoT, such as agricultural activities, resource management, transportation, processing, quality and safety monitoring, and waste generation (Bigliardi et al., 2022; Jagtap, Duong, et al., 2021). An overview of how IoT can support several food operations is presented below.

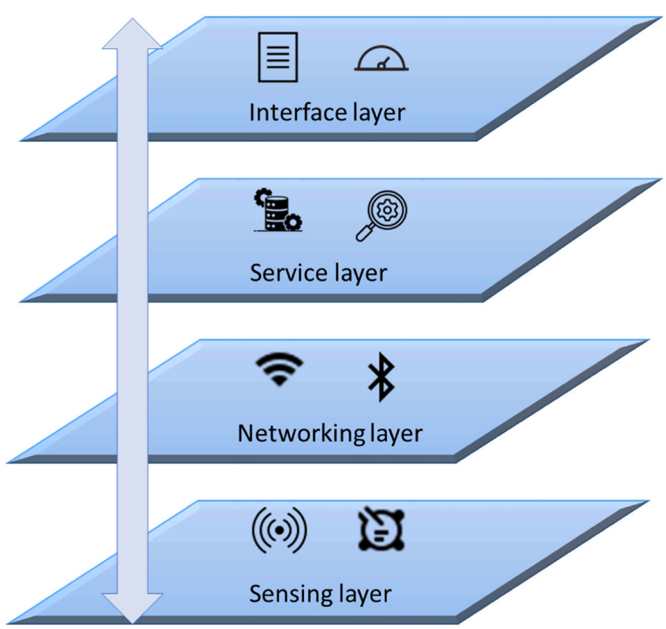

Fig. 5. Four layers of an IoT architecture.

Efficient food production: The amount of data that IoT systems can collect and the speed to share such data allows the optimization of food operations, saving resources, and reducing waste generation. IoT, along with other Industry 4.0 technologies, show several advantages for non-thermal food processing, including energy savings, better environmental performance, lower manufacturing cost, higher level of health and safety during food processing, and better conditions for workers (Jambrak et al., 2021). Retrofitting existing industrial equipment to incorporate IoT technologies is a way to improve food operations and reduce inefficiencies (Panda et al., 2019). This may reduce the cost of installing new machineries that have sensors already incorporated. At the agricultural stage, IoT can be used for chemical (e.g. pesticides and fertilisers) control, crop monitoring, disease prevention, irrigation control, and soil management, among other uses (Navarro et al., 2020).

Food safety: Ensuring the safety of food products is paramount in the food sector. Improved monitoring, by interconnected sensors, helps detecting safety issues in food processing, and therefore reacting to them before the contamination spreads. IoT can therefore detect safety issues more rapidly than traditional methods, and share the corresponding information instantaneously to act without delay. This, in addition to reducing safety risks to a minimum, ensures production is minimally disrupted, saving the use of resources for a batch that would have to be discarded and wasted. For instance, Zhang et al. (2022) and Griesche and Baeumner (2020) explored the use of IoT in combination with biosensors to detect food contamination and release warnings that immediately block supply routes.

The food-safety parameters that researchers have monitored the most with IoT technologies are temperature, humidity, location, and gas presence (Bouzembrak et al., 2019; Dias et al., 2021). These authors also claimed that the most widely used communication technologies in this context are ZigBee, Wi-Fi, radio-frequency identification, and Bluetooth low energy. However, the use of IoT systems in the field of food safety is still rare (Dias et al., 2021). This is mostly due to costs and know how required to set up and manage these systems.

Food quality: As with food safety, IoT can more quickly and precisely find issues related to food quality than with traditional methods. Sensors can identify processing errors or food products with defects and rapidly alert the factory staff to react before more defective products are produced. This is particularly important with the current high-quality standards for food products to meet stringent regulations. Bhatia and Manocha (2021) developed a framework for food quality assessment that acquires real-time data through IoT devices, communicates the collected data to fog nodes backed by the cloud platform, and analyses the data to determine the food quality.

There are several examples of IoT systems that support assessments of food quality. Popa et al. (2019) developed an IoT system to monitor gas, temperature and humidity of packed food products, being able to provide more useful quality information than with traditional quality control systems that focus on weight, volume, and colour and aspect inspection. Sarmah and Aruna (2020) used heterogeneous IoT devices, cloud services, and an Android application, along with a MQ4 gas sensor to detect methane gas, to determine the freshness of food.

4.5. Applications of BD in food processing

BD is defined as large volumes of structured, unstructured or semi-structured data generated from various sources such as sensors, devices, video/audio, networks, log files, transactional applications, web, social media, etc. Nowadays, several manufacturers are analysing large sets of BD and using it to enhance their supply chain performance, and even the food sector is not an exception to this change (Jagtap & Duong, 2019). BD in the food sector is still at initial stage but has attracted attention from both academic and industrial practitioners.

For instance, Jagtap and Duong (2019) demonstrated a case study within a food beverage company where these authors used BD to reduce costs and time for new food product development without affecting taste of the product at the same level of quality than competitor's products. BD is currently being deployed in the food sector for improving transparency and traceability, thereby contributing to sustainable development (Hader et al., 2022; Jagtap, Bader, et al., 2021). Some researchers applied BD within food manufacturing to obtain demand and yield forecast (Magnin, 2016). Another study explored the application of BD in order to reduce food waste (Annosi et al., 2021), while others studied its application in food logistics (Jagtap, Bader, et al., 2021). Fig. 6 shows the application of BD in the food sector.

Food safety: BD technologies are being implemented in the food production that analyse the data generated from smartphones, social media, IoT, and multimedia. Moreover, BD can be used to provide transparency, traceability, and predictive insights of various activities. It helps in making real-time decisions as well as developing the monitoring and sampling strategies for safety evaluation (Jin et al., 2020). BD analytics technology can provide greater predictability to food production operations for the occurrence of foodborne diseases and thwart a potential outbreak in its early stages. Furthermore, this data allows the identification and verification of certain practices or actions that are robust in preventing outbreaks. Similarly, accurate prediction of food products shelf life would be easier as it could be used to determine exact spoilage of product (Astill et al., 2019).

Demand forecasting: BD can support food production operations with new abilities such as demand forecasting. For instance, IBM supported bakeries by using BD to analyse weather data to estimate the demand of certain products based on amount of sunshine, temperature, and consumer preference (Alicke et al., 2016). This also leads to optimized food operations, less food wastage, better planning, and improved resource utilization.

Food waste: Data captured from social media such as Instagram, Twitter, Facebook, etc. can be analysed using BD to formulate policies, which will ultimately reduce food waste. BD can be utilised to uncover previously unknown and valuable insights to reduce waste. For instance, retailers are capitalising BD for waste minimisation using customer complaints made in retail stores (Mishra et al., 2017).

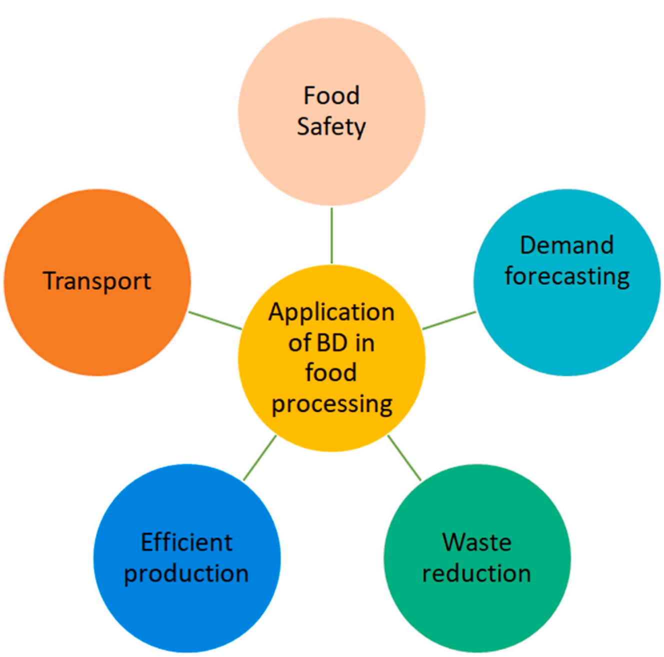

Fig. 6. Application of Big Data (BD) in the food processing.

Efficient production: Tzounis et al. (2017) proposed that application of BD can automate processes, predict situations, and improve food production activities in real-time. It can act as a decision-making tool to provide suggestions, early warnings, and control situations. It can help in maintaining and preserving product quality. For instance, the taste of a product may vary depending on various factors; however, BD analytics can clarify these changes and suggest improvement measures. BD can delve into historical production parameters and identify the optimal settings for a production line. Also, it can reduce the time and cost of launching a new product with minimum impact on product facilities or logistics (Jagtap & Duong, 2019).

5. Novel food processing technologies

The existing conventional food technologies used to ensure microbiological safety of foods and inactivate enzymes, such as sterilization, pasteurization, cooking and drying, result often in degradation of bioactive thermolabile vitamins and polyphenols, as well as oxidation of polyunsaturated fatty acids. At the same time, the growing consumer and market demand for healthier and more nutritious foods that are lightly processed, of high quality and 'fresh-like' characteristics has resulted in the emergence and further development of non-thermal technologies, such as High hydrostatic pressure (HPP), Pulsed electric field (PEF), Ultrasound (US), and Cold plasma (CP). Most of these techniques exert minimal or no effect on essential nutrients and sensory characteristics of food products. These technologies have a potential to partially, or completely, replace the well-known and largely used conventional food processing and preservation technologies (Denoya et al., 2021; Echegary et al., 2022; Hassoun et al., 2020; Jadhav et al., 2021; Sruthi et al., 2022).

In recent years, new non-thermal food processing technologies have emerged (Fig. 3f). These processing technologies are widely studied due to the potential to provide high-quality and safe foods with enhanced nutritional and health-promoting properties. In addition, these green techniques enable sustainable food production with reduced energy costs and environmental impact (Chakka et al., 2021; Pérez-Santaescolastica et al., 2021; Priyadarshini et al., 2019).

HHP is a non-thermal, cold pasteurization technique involving the use of a liquid (normally water) as a medium to transmit the desired pressure (in the range of 300–600 MPa) to a product in a temperature range from 0 °C to 90 °C. The procedure involves sealing a food product in its final packaging followed by submerging in cold or room temperature water within an enclosed vessel (Chakka et al., 2021; Hernández-Hernández et al., 2019; Pérez-Lamela et al., 2021). HHP can successfully inactivate microorganisms by interrupting their cellular function leading to enhanced safety and extended shelf life of foods. Therefore, this technology is mostly used for inactivation of enzymes and pathogenic and spoilage microorganisms including yeasts, moulds, and Gram-positive and Gram-negative bacteria in a wide range of food products, including fresh, processed and canned fruits and vegetables, juices, dairy, meat and seafood (Nie et al., 2022; Pérez-Lamela et al., 2021; Režek Jambrak et al., 2018).

For example, the application of HPP treatment of 200 and 300 MPa was found to be efficient in reducing microbial growth in lean (haddock) and fatty (mackerel) fishes (Cropotova et al., 2020). In another study, it was reported that HPP has the potential to restrict the degradation of phenolic acids and flavonoids and maintain aroma substances of Mandarin (*Citrus unshiu*) juice better than thermal pasteurization (Cheng et al., 2020). Besides the cold pasteurization effect, the use of HHP delays the loss of essential nutrients and undesirable changes of sensory parameters, such as texture, appearance, colour, flavour, and aroma of foods associated with microbial or enzymatic decay (Fernandez et al., 2019). The application of HHP could be also used as a method to enhance the extraction of valuable compounds such as vitamins, polyphenols, proteins, lipids, carbohydrates, and minerals from raw material (Ali et al., 2021a).

PEF is another emerging non-thermal technology, which has gained an increasing interest from the food professionals due to its speed (operates in milliseconds) and wide range of applications. A typical PEF treatment involves the application of short-time electric pulses (1–100 μs) in different ranges of electric field intensities to a food product placed between two electrodes, for a very short duration of time, resulting in reversible and irreversible permeabilization of cell membranes (Arshad et al., 2020; Denoya et al., 2021; Jadhav et al., 2021). Permeabilization of plant cells is normally reversible and occurs under low PEF intensities, resulting in release of intracellular compounds due to electroporation of the cell membrane. This procedure is currently applied to enhance the extractability of valuable compounds from different agri-food and animal-based raw materials. Moderate intensities lead to irreversible permeabilization of both plant and animal cells, while high intensities cause irreversible permeabilization of microbial cells (Ali et al., 2021a; Arshad et al., 2020; Chakka et al., 2021; Hernández-Hernández et al., 2019).

Therefore, the application of high PEF intensities helps to inactivate or inhibit proteolytic and degradative enzymes, spoilage bacteria and other microorganisms in food products, providing safety and maintaining freshness and high quality of food. PEF technology is considered a reliable emerging technology able to ensure a significant microbial inactivation in liquid and semi-liquid foods such as juices, purees, beverages and smoothies with a minor impact on nutritional value, physicochemical quality parameters and number of health-beneficial compounds due to low treatment temperature (Arshad et al., 2020; Cropotova et al., 2021; Režek Jambrak et al., 2018). Similarly to HHP, PEF can also be used for continuous extraction to enhance the recovery of valuable and bioactive compounds from biological tissue (Ali et al., 2021b; Zhao et al., 2019).

However, the antimicrobial effect of PEF depends on both extrinsic factors, such as intensity of electric field, pulse width, duration of treatment, electrical conductivity and pH, and intrinsic factors of microorganisms, such as microbial load, size, type, and growth stage and rate (Zhao et al., 2019). This technology needs some refinement by conducting more economic and engineering studies before it is ready for large scale industrial applications (Chakka et al., 2021; Hernández-Hernández et al., 2019).

US is also a promising non-thermal technology referring to sound waves that exceeds the audible frequency range, i.e. greater than 20 kHz. The main principle of ultrasound is reflection and scattering of acoustic waves originated from molecular movements oscillating in a propagation medium and generating compressions and decompressions, which further result in an increase in mass transfer, turbulence, and production of energy (Bhargava et al., 2021b; Gallo et al., 2018).

Based on the frequency and intensity, ultrasound waves can be divided into two categories: low-energy ultrasound characterized by high frequency (5–10 MHz) and low intensity (<1 W/cm^2) and high-energy ultrasound, having low frequency (20–100 kHz) and high intensity (>1 W/cm^2). High intensity (from 10 to 1000 W/cm^2) and low-frequency (from 20 to 100 kHz) ultrasound is considered disruptive due to detrimental influence on the physical (including structure and mechanical properties), physicochemical and biochemical characteristics of biological materials, in contrast to low-energy ultrasonic waves (Bhargava et al., 2021b; Gallo et al., 2018; Zhao et al., 2019).

Because the cavitation produced by high-intensity US, the technology is being applied in the food industry to inactivate degradative enzymes, eliminate spoilage microorganisms and improve the recovery of valuable compounds from a vast variety of foodstuffs. US can also be used to improve many processing operations, such as emulsification and foaming, freezing and thawing, concentration, drying, tenderization, as well as control and modification of microstructure and textural properties of fatty and protein-rich foods (Ali et al., 2021a; Bhargava et al., 2021a; Gallo et al., 2018; Zhao et al., 2019).

CP has gained popularity in recent years as an alternative food processing technique that can affect the quality attributes of food during treatment and storage, as well as extend food shelf life based on microbial and enzyme inactivation (Pankaj et al., 2018; Sruthi et al., 2022). Plasma may be generated by any kind of energy able to ionize the gases, such as thermal, electrical, light energy, radioactive, and X-ray electromagnetic radiation (Denoya et al., 2021; Pankaj et al., 2018). The mechanism of action of CP on microorganisms can be explained by the impact of reactive species on the microbial cell and damage caused by UV on cellular components and DNA strand break (Hernández-Hernández et al., 2019; Jadhav et al., 2021). The use of CP for microbial decontamination has been extensively researched. For example, CP treatment was found to be effective for postharvest sterilization and preservation of blueberry (Ji et al., 2020). In another study, the application of CP under various processing conditions was investigated on carrot discs, and the results showed a decreased microbial growth in the samples treated at 100 kV for 5 min (Mahnot et al., 2020).

However, there were found many negative effects during treatment of foods due to direct contact between the food and the CP. For example, the ionization produced by CP generates UV irradiation, which increases the content of reactive oxygen species (ROS). Therefore, despite the proven benefits of the application of CP for microbial inactivation in food products, the negative aspects related to the generation of ROS hinder its regulatory approval in the food industry. Other challenges include costs, complexity of equipment and processing parameters, safety of the gases used, and plasma-matrix interactions (Denoya et al., 2021; Hernández-Hernández et al., 2019; Sruthi et al., 2022).

Despite the aforementioned advantages of non-thermal processing, there are still some issues related to consumer acceptance, safety, limited packaging options, and expensive equipment (Chakka et al., 2021; Zhao et al., 2019). At the present time, most of these technologies are applied either on a lab-scale or pilot scale, while a few industrial applications have been seen.

Some relevant examples from studies supporting the reduced environmental impact of emerging technologies are the pasteurization of orange juice with HPP (Cacace et al., 2020), high-pressure homogenization of milk (Valsasina et al., 2017), ultrasound-assisted freeze-drying of apple, carrot, and eggplant (Merone et al., 2020), and PEF pre-treatment for the maceration stage in olive oil and winemaking in relation to conventional processes (Ferreira et al., 2019). However, in terms of processing cost, the use of ultrasound as pre-treatment on freeze-dried apple, carrot, and eggplant was associated with a reduction of 70% in energy consumption in relation to non-sonicated freeze-dried samples (Merone et al., 2020). However, contrasting outcomes in the literature about the economic feasibility among different non-thermal technologies is dependent of food and technology (Aganovic et al., 2017; Cacace et al., 2020), which indicates the necessity of development in the emerging technologies per se.

The progression of processing technologies aligned with these factors is a process that has emerged in recent decades (Chemat et al., 2020). This progressing towards global levels as companies producing the equipment for industrial applications: Hiperbaric based in Spain producing HPP equipment (Hiperbaric, 2021), ELEA producing PEF systems in Germany (ELEA, 2022), Ultratecno producing US systems in Spain (Ultratecno, 2019), and Adtec producing CP equipment in Japan (Adtec Plasma Technology, 2020).

Consequently, the advances in food science generated a parallel development of food processing technologies to the technologies that characterize Industry 4.0 per se (HPP *vs.* IoT, for instance). Since each one of emerging food processing technologies and 4.0 Industry technologies has its own characteristics and applications (indicated in previous sections), seems reasonable to consider that the development of a common area of application between them is necessary to find a harmonious and concurrent evolution. The mutual benefits for food processing from this combination are expected to improve food quality, safety, alignment with consumer preferences and tendencies.

6. Conclusions and future perspectives

There is a high demand for digitalization and automation of various processing operations in the food industry. Especially in the context of the COVID-19 pandemic, it is evident that the time has come to enhance digitalization and automation in the food sector, including food processing, using recent advances and innovations of the fourth industrial revolution (Industry 4.0). In this work, we explored "Food Processing 4.0" concept, utility and effectiveness referring to processing food products in the modern digital era using robotics, smart sensors, AI, IoT, and BD, among other Industry 4.0 technologies. The main advantages of applying the concept of Food processing 4.0 are increased food quality and safety and reduced food waste and impact on the environment, contributing to the green shift in the food processing sector.

Various types of robots are increasingly being deployed in the food industry. The need for automation and robotics has increased in the last two years with the outbreak of COVID-19 pandemic. Many challenges (such as variability in size and shape of foods) stand in the way of automated applications in food processing, preventing widespread adoption of robots. However, recent technological advances in this field, including the design of advanced grippers, have enabled to handle delicate or irregularly shaped food products. Different smart sensors (e.g., spectroscopic-based sensors and electronic sensors) have been developed to be used in various applications. For example, in the food packaging, the use of smart sensors has the potential to improve food quality and safety and communicate useful information to consumers. Recent trends of miniaturization and portability, as well as scientific advances in certain fields, such as nanobiotechnology have led to the development of efficient and cheap smartphone-based sensors.

AI is one of the most powerful tools that can be used to solve complex problems and perform various tasks (such as food sorting, quality and safety check, and process optimization) in the food processing, accelerating the move toward an intelligent food processing. Although AI has already transformed some areas of manufacturing and food processing environments, it is expected that more AI-based applications will be introduced in many more areas in the near future.

Slowly, but surely, the food processing industry is getting acquainted with IoT and other related technologies. Food quality, safety and logistics can be enhanced and food waste and food production cost can be reduced by the implementation of IoT-based technologies. Based on this literature review, it was possible to observe a growth trend in the number of publications related to IoT in food processing. IoT provides opportunities to improve food processing through strengthening supply chain transparency by real-time monitoring and tracking production, distribution, and storage of food products. IoT technology could be a game-changer for future food processing and other food industry sectors once technical, operational, financial, and other related challenges are met.

Another Food Processing 4.0 enabler that was discussed in this review is BD that is paving its way to revolutionize the food industry. Implementing data analytics tools in the food industry offers many benefits, including among others, food safety, demand forecasting, real-time decision making, and food waste management. However, some barriers, related to lack of system standards, limited shared data, data security, and legal issues, are still hampering the full exploitation of BD in the food production.

Innovative food processing technologies (e.g., HPP, PEF, etc.) are increasingly adopted in the food industry given their desirable features (such as energy efficiency, and time and resource saving) that are fully aligned with Industry 4.0 principles. These emerging technologies are of paramount importance to meet consumer's demands for minimally-processed food with high nutritional and sensory quality. However, many factors (including among others, consumer acceptance, benefits and risk, high initial investments, and regulatory frameworks) that are impacting the adoption of these novel technologies by food processing industry, need to be considered and thoroughly analysed.

In short, more research focusing on a wider utilization of Industry 4.0 innovations and aligned with emerging food processing technologies is expected in the near future, allowing to overcome current shortcomings, thus supporting the transition to a smarter and more sustainable food processing. Although Food Processing 4.0 enablers bring great opportunities and significant improvements to the food industry, they also create challenges that need to be tackled.

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Declaration of interest form

The authors declare no conflict of interest.

Data availability

No data was used for the research described in the article.

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