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Creating new opportunities for sustainable food packaging through dimensions of industry 4.0: New insights into the food waste perspective

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ABSTRACT

Background: Non-biodegradable food packaging (mainly plastic) and food waste are two major concerns that cause severe environmental and economic challenges as well as potential human health and food insecurity risks. Therefore, intensive efforts are being devoted to transforming food production and consumption patterns and developing alternative technological solutions to alleviate such issues.
Scope and approach: This review intends to discuss the interplay between food packaging, food waste, and sustainability. Some common strategies used in food packaging are briefly summarised. The significance of nano-biotechnology, smart sensors, and other fourth industrial revolution (Industry 4.0) innovations is emphasized, focusing of the role of these smart technologies in the emergence of novel prospects, such as the development of active and intelligent packaging systems. In addition, insights on consumer acceptance of novel packaging materials/technologies are given and conclusions are drawn.
Key findings and conclusions: Several innovative food packaging solutions based on Industry 4.0 technologies are being developed, changing the way food is packed and consumed. Indeed, growing evidence shows that digital technologies (particularly artificial intelligence, big data, blockchain, and 3D printing) will have a greater impact on food packaging in the sense of "Packaging 4.0". However, more research is still needed to fully harness the

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benefit of advanced technologies, enabling them to overcome current barriers and achieve a healthier and more sustainable food future.

1. Introduction

Food packaging plays a vital role in the food industry by protecting food from pathogens, chemicals, and physical damage during transport and storage. However, a considerable amount of plastic waste is generated every day by the modern "throw-away society," and a significant part of these plastics is attributed to food packaging. Food plastic packaging is becoming of particular concern due to its disastrous environmental impact and potential human health effects. Indeed, synthetic plastic materials are hardly self-degradable and cause greenhouse gas (GHG) emissions in addition to their possible release to packaged food compromising food quality and safety. Thus, developing new packaging materials to create sustainable and multifunctional food packaging is deemed necessary (Cheah et al., 2023; Fogt Jacobsen, Pedersen, & Thøgersen, 2022; Sadeghi, Kim, & Seo, 2022).

With around one-third of food intended for human consumption never getting eaten, food waste and loss is another major global issue that contributes to the unsustainability of food systems, causing environmental, economic, and social problems. Therefore, using by-products and side-streams to produce food packaging films and coatings seems to be a promising win-win strategy to decrease the environmental impact of food waste and food packaging and enhance food systems (Capanoglu, Nemli, & Tomas-Barberan, 2022; Mateus et al., 2023).

In recent years, alternative food packaging solutions are being investigated using a wide range of renewable raw materials and food by-products. For example, various polysaccharides, proteins, and lipids from waste biomass can be used in the development of green packaging solutions (Priya, Thirunavookarasu, & Chidanand, 2023). The role of bio-based and bio-degradable polymers, including synthetic (e.g., polylactic acid), microbial (e.g., microbial polyesters and bacterial cellulose), and natural (e.g., alginate and casein) polymers in food packaging was also highlighted (Nilsen-Nygaard et al., 2021). The development of such packaging alternatives has been enhanced by the emergence of advanced technologies. Novel technologies entail promising potential to prevent or reduce food loss and waste through the use of innovative processing techniques and applications in smart packaging (Khalid & Arif, 2022). Particularly the fourth industrial revolution (called Industry 4.0) innovations could reduce food waste, enhance food safety and quality, and help develop new and healthier foods (Hassoun, Prieto, et al., 2022). Smart technologies including artificial intelligence (AI), big data, robotics, smart sensors, the Internet of Things (IoT), 3D printing, cybersecurity, and blockchain are increasingly being adopted in the agri-food industry (Hassoun, Aït-Kaddour, Abu-Mahfouz, et al., 2023; Hassoun, Bekhit, et al., 2022), yet scarcely studied in the frame of food packaging.

Although the use of some of these technologies in food packaging has recently been reviewed (Sadeghi et al., 2022), insights into the food waste perspective are still missing. Other recent review papers have only focused on the role of specific Industry 4.0 components (such as 3D printing, IoT, or nanotechnology) in the reduction of food waste and the development of new food packaging systems. For example, the implication of 3D printing in creating innovative engineering solutions based on food waste-based materials was highlighted by Yu and Wong (2023). Another recent review underlined the need for IoT in the food processing sector, including the food packaging (Dadhaneeya, Nema, & Arora, 2023), while the potential of using big data-based systems in food safety was demonstrated by Jin et al. (2020). The involvement of nanotechnology and nanomaterials in developing smart food packaging was also reported in recent publication (Azman, Khairul, & Sarbon, 2022; Mahmud, Sarmast, Shankar, & Lacroix, 2022).

However, to the best of our knowledge, no review has focused on the role of Industry 4.0 technologies in food packaging with respect to food waste reduction. Therefore, the main objective of this review is to highlight, through a comprehensive review of the scientific literature, recent advances regarding the valorisation of food waste in packaging by harnessing the power of technology and advanced innovations, especially those of Industry 4.0, focusing on the results of the most recent studies to improve food chain sustainability.

2. Interplay between food waste upcycling and sustainability

The concept of food waste upcycling is growing in the food industry. From farm to fork, edible food can be lost during production and postharvest, distribution and retails, and food services/home surplus and leftovers. Global food wastage is a substantial economic (about USD 1 trillion each year) and environmental (generating annually about 3.3 billion tons of CO_2, or about 8% of global GHG emissions) burden (Capanoglu et al., 2022). Therefore, innovative strategies for food waste management are deemed necessary to ensure food security and financial and environmental benefits.

Preventing food waste relies on avoiding the production of food waste and the surplus of food. Raising public awareness about the drawbacks of food waste on the environment could contribute to the optimization of storage and inventories (Burlea-Schiopoiu et al., 2021). Furthermore, campaigns to promote waste-reducing behaviours could be achieved by implementing educational programs. In the case of food surplus, redistribution and donation enable the reuse of food products without further processing, thus playing a dual objective for food security and sustainability.

Furthermore, advanced sustainable process design could produce stable, high-quality products and limit waste generation (Hassoun, Boukid, et al., 2022). The selection of packaging materials is crucial for food protection and quality preservation. Unlike traditional packaging (e.g., plastic), recyclable packaging aligns with 4 goals of the 2030 Sustainable Development Goals (i.e., Goal 11, Goal 12, Goal 14, and Goal 17). In addition, smart packaging (artificial and active) could support shelf-life extension and safety improvement, thus supporting sustainability (Boukid, 2022). Improved storage infrastructure and cold chain management could reduce food loss during transportation and storage. Retailers can proactively reduce food waste via better storage control, planning, and traceability (Nunes, Rocha, Riesenegger, & Hübner, 2022). To avoid food spoilage, food services (hotels, restaurants, and catering) must ensure proper storage and regular inventory (Dhir, Talwar, Kaur, & Malibari, 2020).

By 2030, the United Nations Sustainable Development Goal 12 (SDG 12) targets 50% food waste reduction throughout the supply chain. The reduction strategies start with crops and livestock production (Fig. 1). Proper agricultural practices during crop/animal growth, harvest, and postharvest could be achieved by adopting smart technologies, such as artificial intelligence and sensors. In combination with traceability, improved storage and handling have a substantial positive effect on reducing waste. For the ingredients and food production, opting for a zero-waste approach could reduce the cost of waste management and benefit the environment.

Consumers also play pivotal roles in food waste management and sustainability, and therefore, communication and education can improve their acceptability of upcycled foods (Aschemann-Witzel, Asioli, Banovic, Perito, & Peschel, 2022). Transparency of the production process of upcycled foods can boost consumers' awareness and willingness to consume/pay (Teigiserova, Hamelin, & Thomsen, 2020).

Conventional and innovative strategies can increase waste food upscaling (Fig. 2). Traditionally, recovering food waste is a common practice to produce low-value feed and fertilizers (Santagata, Ripa, Genovese, & Ulgiati, 2021).

Currently, animal feed made via insects and fungi waste bioconversion is gaining interest as a sustainable approach to reduce GHG emissions, land use, and deforestation (Boukid et al., 2021, 2022). Similarly, various food wastes have been transformed into compost rich in nutrients for soil fertilization (Chen, Zhang, & Yuan, 2020).

Driven by sustainability and economic gains, repurposing surplus food, food by-products, and food waste toward producing high-value-products is trending upwards. New foods made using food by-products were reported to have desirable nutritional and organoleptic features. For instance, numerous nutritious bakery products were fortified using chestnut peels, wheat bran, almond skin, apple pomace, grape pomace, and artichoke waste (Pasqualone, Laddomada, Boukid, de Angelis, & Summo, 2020; Rainero et al., 2022). Furthermore, food waste can be further processed for nutrient recoveries, such as carotenoids, vitamins, and antioxidants. These compounds can be used as food supplements and/or valuable functional additives, such as pectin, enzymes, and cellulose (Najari, Khodaiyan, Yarmand, & Hosseini, 2022). Fermentation is a viable green process to valorise food waste for different purposes. Agri-food industry wastes can produce high-value biomass as a cheap substrate for fungi, yeast, and bacteria.

Furthermore, fermentation can improve these substrates' texture, taste, flavour, and nutritional value for various food applications (Boukid et al., 2023). Through fermentation technology and synthetic biology, new biomaterials, such as polylactate (PLA) and polyhydroxyalkanoates (PHA) can be produced from agro-industrial residues (e.g., sugar and starch industry by-products) and household waste. For energy recovery, anaerobic co-digestion can convert food waste into biogas, such as methane, that can be used to generate electricity and heat (Suarez, Tobajas, Mohedano, & de la Rubia, 2022).

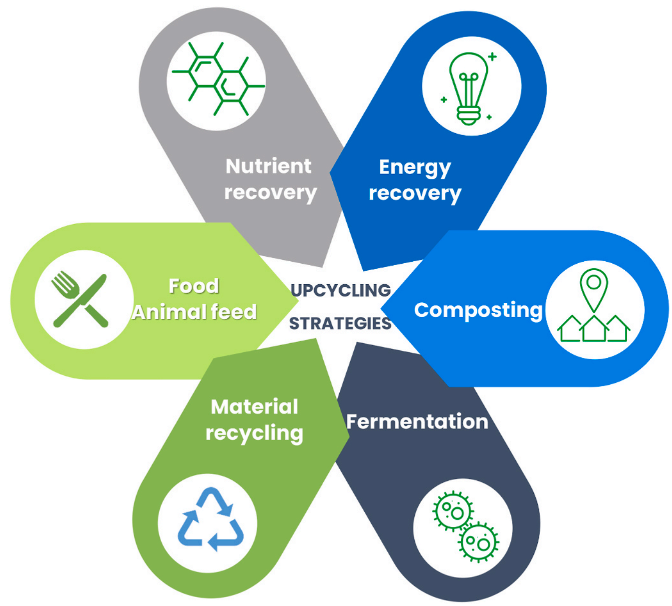

Fig. 2. Strategies for the upcycling of food waste.

3. Common food packaging strategies

A wide range of bio-based and petroleum-based polymers have been used in various biodegradable and non-biodegradable packaging materials. Polymers employed in food packaging can be synthetic or of microbial or natural origins (Alias, Wan, & Sarbon, 2022; Nilsen-Nygaard et al., 2021).

3.1. Synthetic polymers

Most of the commercially available food packaging polymers, such as Polyethylene (PE), Polypropylene (PP), Poly(ethylene terephthalate) (PET), Polystyrene (PS), Poly(vinyl chloride) (PVC), and Poly(vinylidene chloride) (PVdC) are derived from petrochemicals. Polymers of olefins are a class of unsaturated hydrocarbons covering at least one carbon-carbon double bond in their chemical structure. PE and PP are among the most used polyolefins in food packaging due to their low-cost and other desirable features, including toughness, flexibility, and easy processability (Alias et al., 2022; Tyagi, Salem, Hubbe, & Pal, 2021).

Research shows that barrier properties, especially those related to gas and moisture of such polymers are among the most important characteristics in designing films and coatings. It should be highlighted that the barrier properties of these polymers can be influenced by various factors including, among others, polarity and chemical structure (Trinh, Chang, & Mekonnen, 2023; Tyagi et al., 2021). For example, due to its poor O_2 and moisture permeability, PS is occasionally used in packaging fresh products. A stable and homogenous material of PS, namely expanded polystyrene (EPS), is applied in yogurt and dairy product (Guazzotti et al., 2022), egg cartons, meat trays, and disposable crockery (Semple, Zhou, Rojas, Nkeuwa, & Dai, 2022).

Fig. 1. Examples of strategies for reducing food waste.

Due to environmental and health concerns about the aforementioned synthetic plastic polymers, many studies have recently focused on developing synthetic bio-polymers such as PLA and PHA (Nilsen-Nygaard et al., 2021; Trajkovska Petkoska, Daniloski, D'Cunha, Naumovski, & Broach, 2021).

3.2. Microbial polymers

Growing research shows the benefits of using of a variety of microbial polymers such as pullulan, gellan, curdlan, kefiran, levan, bacterial cellulose, and bacterial alginate in the development of food packaging (Perveen et al., 2023; Zikmanis et al., 2021). A few examples of these microbial polymers will be presented in this section.

Pullulan is one of the most widely used polysaccharides because of its high-water solubility, non-toxicity, and oxygen barrier properties, which are probably due to its specific structure composed of α-(1, 6) repeated maltotriose units via α-(1, 4) glycosidic bond. These advantageous characteristics acknowledged pullulan as an edible "active" coating with a Generally Recognized as Safe (GRAS) status (Zikmanis et al., 2021). The potentiality of pullulan as a coating substance to extend the shelf life of bananas (Ganduri, 2020) and litchi (Kumar, Neeraj, & Singla, 2020) has been investigated.

Gellan gum is an extracellular heteropolysaccharide produced by bacteria *Sphingomonas elodea*. This polymer is soluble in water and has excellent colloidal and gelling properties (Zikmanis et al., 2021). It is often blended with other polymers to improve mechanical and other relevant properties of the packaging. For instance, gellan gum was added at 10 and 20 % in starch blends to enhance the tensile and barrier properties of the packaging films (Sapper, Talens, & Chiralt, 2019). In another study, a colorimetric H_2S sensor based on silver nanoparticles was synthesized by using gellan gum to control meat spoilage in intelligent packaging (Zhai et al., 2019). The results showed a good stability of this intelligent packaging during storage under basic conditions due to its negatively charged surface resulting from the gellan gum.

In a similar study, gellan gum was incorporated with mulberry anthocyanins in bilayer colorimetric films to monitor crucian freshness in real-time (Yang et al., 2021). The developed film was found to be a safe, low-cost, and non-destructive indicator for monitoring the fish spoilage during storage. In a recent study, gellan gum-based functional films were integrated with **bacterial cellulose** and metal nanoparticles to investigate the possibility of improving the shelf life of fresh-cut pepper (Chen et al., 2023). The obtained findings demonstrated that the developed active packaging had excellent anti-fogging, bending, and thermal reversibility properties and was able to reduce softening, reddening, browning and rotting of the samples during storage.

The potential of **curdlan**, a homopolysaccharide produced by *Alcaligenes faecalis* and *Agrobacterium* sp. has also been examined in various studies, especially when blended with other polymers (Zikmanis et al., 2021). For example, edible food packaging films were prepared by mixing different ratios of curdlan and **xanthan**; a polysaccharide obtained from the fermentation of sugars by *Xanthomonas campestris* (Mohsin et al., 2020). The optimized synthesis of xanthan/curdlan blend films improved their overall water solubility and tensile strength, confirming its potential use as food packaging material. In another study, a blending film was prepared using curdlan, polyvinyl alcohol, and thyme essential oil, resulting in an improved quality and extended shelf life of chilled meat due to increasing mechanical and water vapor barrier properties of the packaging film (Zhang et al., 2020).

3.3. Natural polymers

Natural-based polymers are ubiquitous materials that can be sourced from various natural origins with large molecular weights. Natural polymers can be categorized according to their source in plant-, animal-, and microbial-derived polymers.

Based on the chemistry of their polymeric materials, natural polymers can be divided into several classes, including polysaccharides, proteins, polyamides, and polyesters-based polymers (Fig. 3). Compared to synthetic polymers, these naturally occurring polymers present desirable features such as low cost, ample abundance, biocompatibility, biodegradability, mechanical properties, renewability, and diverse functionalities (Khalid & Arif, 2022).

Recently, growing consumer preferences towards new and more sustainable food packaging materials have led to have led to intensive search for natural polymers (Mateus et al., 2023). However, a few drawbacks of natural polymers can be pointed out such as their high cost, low mechanical performance, and high moisture/oxygen permeability limitations.

Several solutions have been suggested to overcome the limitations of these polymers. Among the studied strategies is the use of blending and multilayer assemblies. For example, the mechanical properties of cellulose were improved by the infusion of bio-based particles, such as lignocellulosic fibres (Khalid, Al Rashid, Arif, Ahmed, & Arshad, 2021). Moreover, chitosan, which presents excellent antimicrobial activity and film-forming properties, is commonly mixed with other natural polymers (e.g., proteins and lipids) to improve its functionality as a packaging material. Additionally, starch is a natural polymer, extensively used due to its sustainability, abundance, and biodegradability, and its mechanical and thermal properties can be improved by blended modifiers and/or polymers (Lauer & Smith, 2020). The use of nanocomposite fabrications and other technological innovations (as will be discussed in the following sections) have also been suggested to enhance barrier properties and overcome the permeability constraint.

4. Overview of fourth industrial revolution (Industry 4.0) technologies

Food Industry 4.0 is a multidisciplinary area centred on the instantaneous and massive interconnectivity between humans and devices, management of information, and the use of smart systems (Hassoun, Aït-Kaddour, Abu-Mahfouz, et al., 2023; Hassoun, Jagtap, Trollman, et al., 2023). The progress made in Food Industry 4.0, including among others Quality 4.0 (Hassoun, Jagtap, Garcia-garcia, et al., 2023), Traceability 4.0 (Hassoun, Abdullah, et al., 2022; Hassoun, Kamiloglu, Garcia-Garcia, et al., 2023), Processing 4.0 (Hassoun, Jagtap, Trollman, et al., 2023), Dairy 4.0 (Hassoun, Garcia-garcia, Trollman, et al., 2023), and Meat 4.0 (Echegaray et al., 2022) is expected to aid in creating new solutions for improved food packaging and preservation. The enabling technologies that lead the way in this area include nanotechnology, smart sensors, robotics and automation, AI, big data, IoT, and blockchain (Fig. 4).

Nanotechnology is one of the critical tools to advance in developing systems and strategies for food preservation and safety. The nanomaterials (at least one dimension is comprised between 1 and 100 nm) have improved surface area and facilitated mass transfer, enhancing their properties in terms of diffusivity, solubility, and bioaccessibility, among others. There are several new materials and structures produced at the nanoscale, such as nanoliposomes, nanoemulsions, nanocomposites, nanohydrogels, and nano solid lipid particles. Nanotechnology can be seen as one key supporting technology to tailor the properties of food packaging materials and align them with modern consumption trends and sustainable advances (Azman et al., 2022; Capanoglu et al., 2022).

Smart sensors are vital tools of Food Industry 4.0 by acquiring data on freshness, humidity, contamination, and cracks, facilitating the control of processes. The use of sensors in packaging is derived from the combination of their two predecessors: intelligent and active packaging. Intelligent sensors share information about a specific modification in food composition or a packaging system's micro-environment during product shelf-life (Amin et al., 2022; Liebig et al., 2023). Some of the most studied intelligent sensors are centred on detecting changes in food pH, fluctuations in storage temperature, and accumulation of volatile

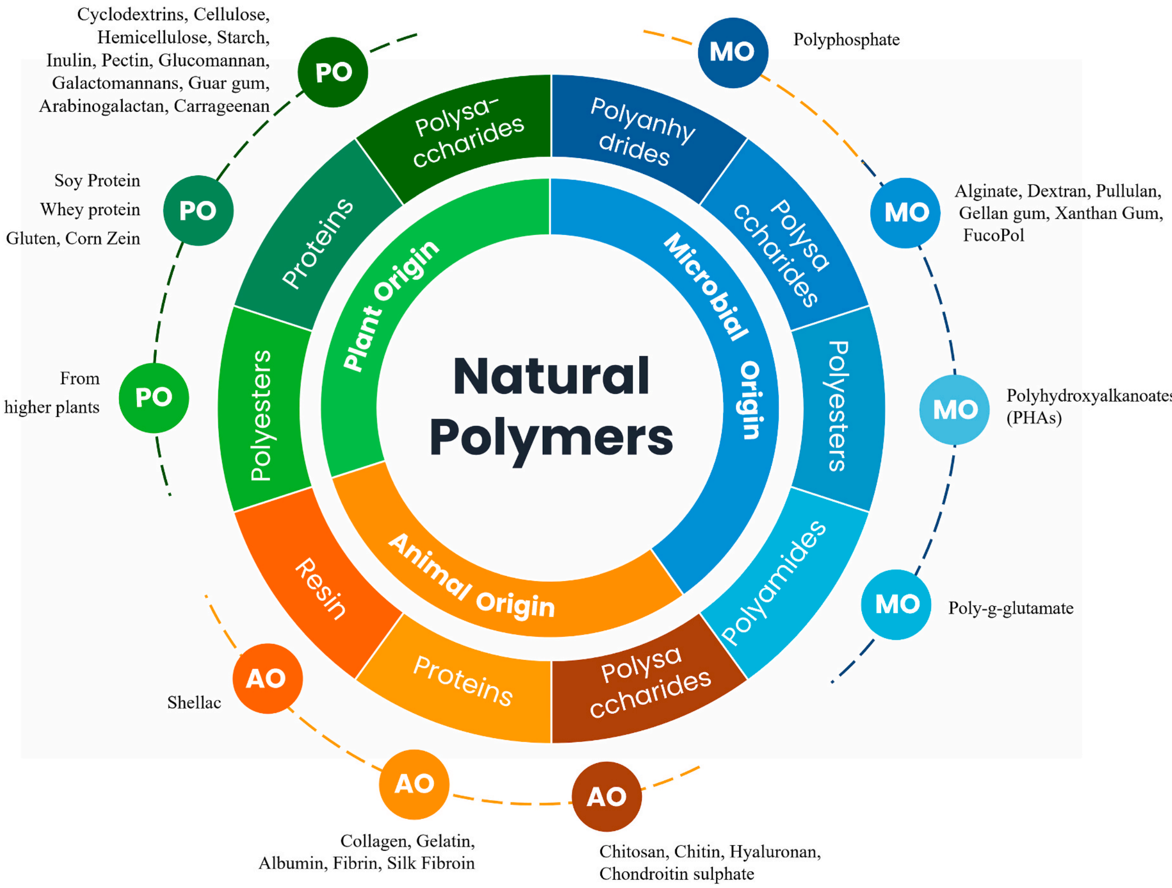

Fig. 3. Classification of natural polymers (AO: animal origin; MO: microbial origin; PO: plant origin).

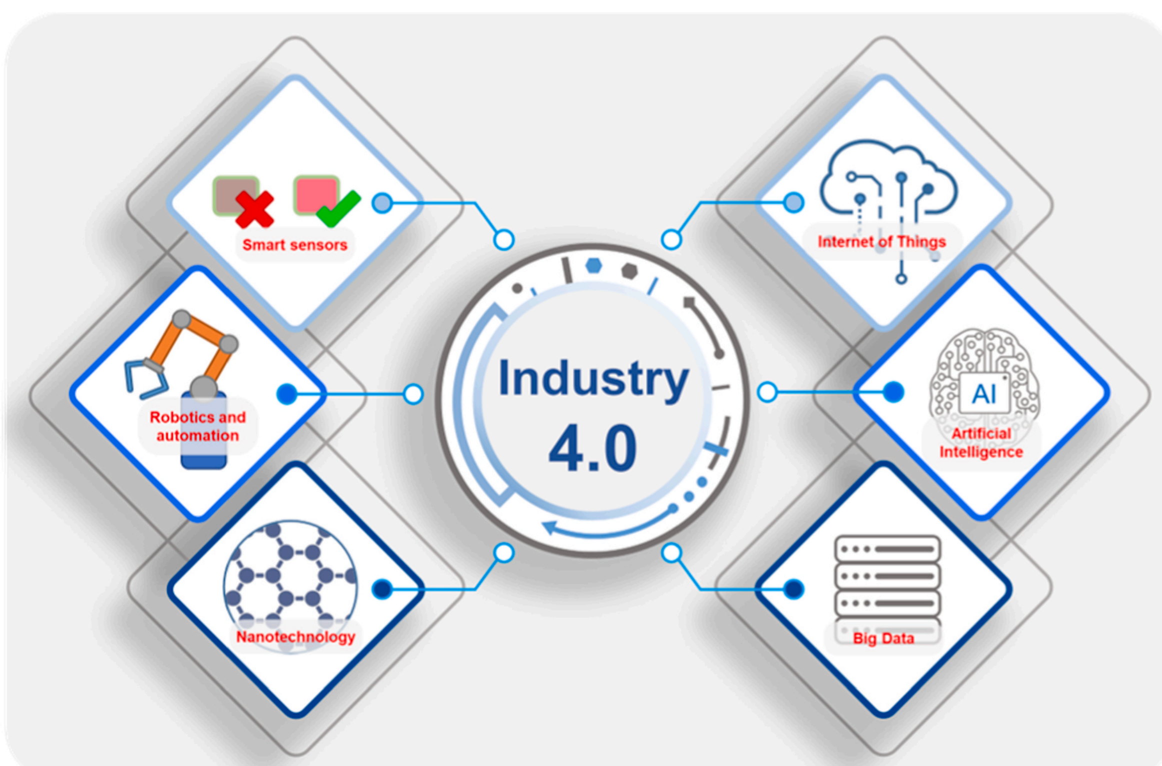

Fig. 4. Main tools of Food Industry 4.0 for food packaging and preservation (clock-wise direction): IoT, AI, big data, nanotechnology, robotics and automation, and smart sensors.

compounds containing nitrogen (Azman et al., 2022; Duan, Li, Wang, Lin, & Wang, 2023; Yousefi et al., 2019). As a result, intelligent sensors are intended to monitor and sense changes and food conditions and display its information, significantly increasing food's shelf-life, traceability, and safety (Amin et al., 2022; Trinh et al., 2023). On the contrary, active sensors contain active compounds that will interact with food or the micro-environment of the packaging system to provide functional attributes in addition to the barrier and delay expected changes during storage. A vast diversity of compounds with antioxidant and/or antimicrobial have been explored in food areas along with absorbers of volatile components (humidity, oxygen, or ethylene, for instance) or release of gases, such as carbon dioxide (Azman et al., 2022; Trinh et al., 2023).

The use of **robotic and autonomous systems** in food processing operations is characterized by many aspects that favour their incorporation and continuous evolution in modern industries: arrangement to improve the dynamics and productivity of process; control to execute tasks under specific conditions; dexterity to carry out complex operations in a fast and skilfully way; hygiene to reduce the risk of contamination and loss of food safety; easy operation and maintenance to facilitate the daily human-machine interaction (Konfo et al., 2023). Furthermore, the vast possibilities to tailor the system can fit food processing by providing solutions, e.g., to pick-and-place operations (Wang, Or, & Hirai, 2020).

AI can be defined as a digital tool aiming to simulate the human capacity to interpret information and reach a decision utilizing integrating different digital systems. In other words, computer programs can reason and conclude to achieve a goal (Nunes et al., 2023). AI has evolved into more complex systems and more efficient computing devices from the rudimental and initial steps of its creation and conceptualization. Nowadays, AI comprises many algorithms, including fuzzy logic, machine learning, artificial neural network (ANN), and decision trees. The main advantages of using AI in food production and preservation are the capacity to assist in the decision-making process and prediction of variables from complex and big databases that conventional programming systems cannot return a response in a reasonable time or for an operation that are too costly to be performed (Mavani et al., 2022).

The **IoT** is a crucial technological resource of the Food Industry 4.0. It is an interlinked network that collects and exchanges digital data between computing systems, sensors, actuators, and other digital devices. This essentially clarifies the name and the two primary components of this tool: "Internet" and "Things." (Dadhaneeya et al., 2023; Kodan, Parmar, & Pathania, 2020). The versatility of this tool is one of its main attributes due to its customizable architecture that can be composed of functional elements known as *Devices* (physical components involved in the sensing and actuation), *Communication* (data link layer where information is transmitted among elements); *Services* (supporting functions to assist in the discovery of new devices connected to the network, analysis of data, and control of devices, for instance); *Management* (governance of IoT system and manage the actions executed by each element); *Security* (layer responsible for the reliability of the network by checking the authenticity of information and authorizing the access to information, preserving the privacy of data, and verifying the integrity of information, among other actions); and *Application* (is the layer that enables the interface for interaction between users and the network, which mainly aims to monitor system status and control it) (Mayer & Baeumner, 2019; Ray, 2018). Therefore, transparency, efficient management, improved traceability, authentication of quality characteristics, and monitoring of information for stakeholders and consumers can be cited as crucial aspects for the application of IoT in the food area. Moreover, IoT can also strengthen consumer trust in food product quality and industrial processing for information indicated on labels or quality perceived by claims for specific shares of the food market (Rejeb, Rejeb, Zailani, Treiblmaier, & Hand, 2021).

The fast growth and massive data generation and sharing (composed of multiple formats) became an overwhelming task for traditional computational systems and algorithms, hence the emergence of **big data** analytics. Recent research shows the necessity to collect and analyse data to obtain comprehensive and meaningful information from the bulk of data. Big data is the tool of the fourth industrial revolution that can effectively manage this complex task (Jin et al., 2020). Essentially, the big data tool is characterized by the 5Vs that can deal with large datasets (Volume); take into account the accuracy of information (Veracity); manage information from different formats and presentations (Variety); it is capable of acquiring, process, and storage immense in a defined period of time (Velocity); and the discovery of patterns, relations among indicators, and other helpful information (Value) (Liu & Zhang, 2020). For instance, big data can assist in understanding human perception of food packaging and characterize the felling and attitudes towards the type of packaging, the composition, and the progression of trends from data in social media for the general population (Ganczewski & Jemielniak, 2022). Furthermore, big data analysis can reveal the gaps in current packaging and help designing upgraded new versions (Gao, 2021). A schematic representation of the application of Food Industry 4.0 in food packaging and preservation is presented in Fig. 5.

5. Implication of Industry 4.0 technologies in reduction and valorisation of food waste to develop novel packaging solutions

5.1. Nanotechnological and biotechnological advanced solutions

Nanotechnological and biotechnological solutions can play a significant role in reducing and valorising food waste to develop novel packaging. Nanotechnology can be used in packaging to improve the barrier properties (by providing barriers to moisture and controls gaseous exchange), mechanical strength, and shelf-life of food products (Mahmud et al., 2022; Trajkovska Petkoska et al., 2021). For example, nanoparticles can be added to polymers to create nanocomposites that improve the gas barrier properties of packaging materials. This helps to reduce food waste by extending the shelf-life of food products. Nanocellulose-based packaging is another approach that uses nanotechnology-based in the food industry. Nanocellulose is a nanoscale fibre derived from plant material that can be used to create biodegradable and compostable packaging materials. These materials can replace traditional plastic packaging, reducing waste and pollution (Harrison et al., 2023).

Nanosensors are miniaturized devices that utilize nanotechnology to detect and measure specific parameters with high sensitivity and accuracy. The use of nanosensors can detect changes in the food environment such as temperature, humidity, and gas composition as well as product quality monitoring, contaminant detection, and packaging integrity. Overall, nanosensors offer a powerful tool for real-time monitoring of food environments, enabling proactive measures to maintain food quality, extend shelf-life, and enhance food safety (Azman et al., 2022). However, it is important to ensure the safety and regulatory compliance of nanosensor technology in food applications to address any potential concerns regarding the release of nanomaterials into the food chain. Proper risk assessments and regulations should be in place to address any potential environmental and health concerns associated with the use of nanomaterials in agricultural industry.

Biotechnology involves the use of biological processes and organisms to create sustainable and eco-friendly packaging materials. For example, bioplastics made from renewable resources, such as starch, cellulose, and sugar can be used as an alternative to petroleum-based plastics (Cheah et al., 2023). These bioplastics can be biodegradable, compostable, and recyclable, reducing the environmental impact of packaging waste. Enzymes can also be used to break down food waste into useful products, including biofuels or fertilizers. This can help reduce the environmental impact of food waste and create a more sustainable food system. Antimicrobial agents have been also added to intelligent and smart packaging materials to prevent the growth of microorganisms that

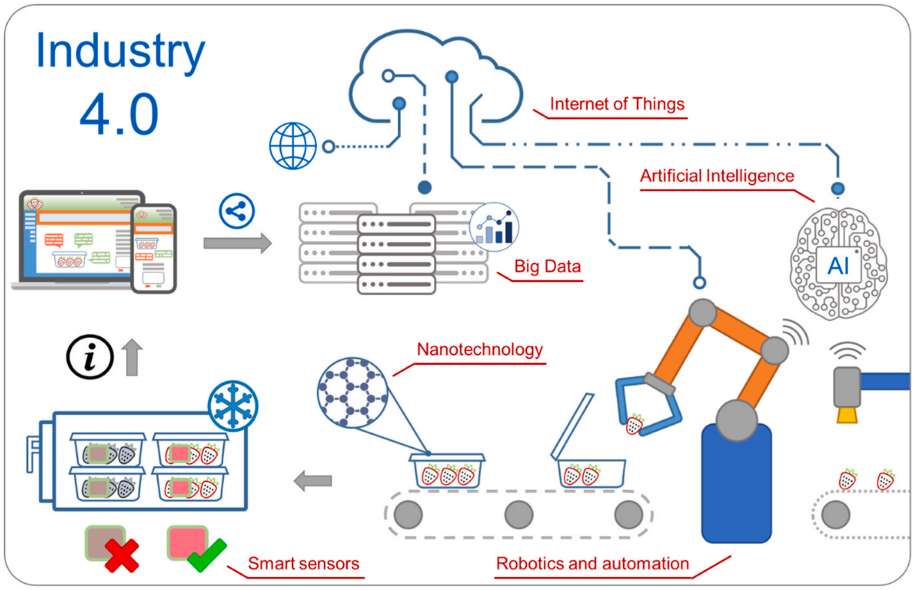

Fig. 5. Schematic representation of Food Industry 4.0 tools in food packaging and preservation.

cause spoilage and foodborne illness (Rathod, Bangar, Šimat, & Ozogul, 2023). Another kind of electronic information-based smart packaging systems is RFID, which is a communication tool. RFID is an auto-recognition system that uses cordless sensors to designate segments and gather real-time data; it does not fall under any of the categories of markers or sensors (Mondal et al., 2019).

5.2. Smart sensors

Active packaging uses components inserted into the packaging to increase shelf-life, while intelligent packaging uses molecules to monitor storage conditions and detect and alert the consumer on spoilage or food deterioration issues (Yousefi et al., 2019; Zheng, Liu, Yu, & Shao, 2022). Many publications have shown great potential to implement smart sensors in smart food packaging (active and intelligent packaging).

Natural components, such as natural pigments (e.g., anthocyanins, betalains, carotenoids, chlorophyll, and curcumin), polyphenols, tannins, and polymer carriers (e.g., chitosan, gum, and starch) have been widely used in smart packaging systems. However, due to natural resource constraints and current sustainability goals, recent research aims to use and extract such valuable compounds from food waste and food processing by-products, such as peel, pulp, husk, seeds, bagasse, barks, and oil cake, among others (Hamed, Jakobsen, & Lerfall, 2022). For example, kiwi agricultural waste and industry by-products have high content of bioactive compounds (such as phenolic compounds, vitamins and carotenoids) that can be used in many applications, including smart food packaging (Chamorro et al., 2022).

Smart packaging based on food waste extracts has been reported to detect changes in pH, humidity, time/temperature, CO_2 or other gas production, and microbial growth (Amin et al., 2022; Bhargava, Singh, Mor, & Kumar, 2020; Yousefi et al., 2019). Sensors (e.g., time-temperature, humidity, and gas sensors) and indicators (e.g., pH-responsive indicators) are considered among the most important intelligent packaging tools (Cheng et al., 2022; Zheng et al., 2022). Optical sensors represent an interesting option for application in intelligent food packaging due to their potential to sense non-destructively and the possibility to straightforwardly visualize any changes in the product quality though transparent packaging (Yousefi et al., 2019). For example, natural pigments like anthocyanin have been widely used to monitor food freshness as they change their colour upon pH variations of food during distribution and storage (Roy & Rhim, 2021). In this context, bio-based films were developed using waste from blueberry and blackberry pomace, incorporated in chitosan-based matrix (Kurek et al., 2018). The developed smart chitosan films were characterized by active and intelligent properties due to the presence of respectively antioxidants and anthocyanins in the incorporated blueberry and blackberry pomace extracts.

5.3. Digital tools as part of industry 4.0 technologies

Digital technologies can also eliminate waste by assessing the best practices for remanufacturing and recycling. Circular economy (CE) operates on the principles of regeneration, keeping materials in use while reducing waste. It is also important to find options to develop new packaging solutions that could ultimately enhance the implementation of CE. The incorporation of Industry 4.0 dimensions and enablers (especially digital tools, including AI, big data, 3D printing, and blockchain) in the food packaging sector is referred to as Packaging 4.0. The application of such advanced technologies is essential in the reduction of food waste and food loss, as well as in the valorisation of food waste (Fig. 6).

5.3.1. Role of artificial intelligence (AI)

AI is at the forefront of the ongoing digital revolution that the food industry, like other industries and manufacturing processes, is experiencing in almost every aspect of its operations, including the way food is packaged. Growing evidence shows that AI has a big potential to improve food packaging and reduce food waste by enhancing food safety, and extending food shelf-life, increasing transparency along the food supply chain management system (Kumar, Rawat, Mohd, & Husain, 2021). AI can be used to create consumer-friendly packages and predict consumer satisfaction with the developed food packaging solution. For example, machine learning models were proposed to investigate the possibility of performing an automated evaluation of food packaging (Parcesepe et al., 2022). The authors applied a multi-layer perceptron ANN model to analyse results of an online survey about some food and beverage packaging, and the results showed a high correlation between the package characteristics and the customer appreciation of the package. An AI tool called k-nearest neighbor (KNN) algorithm, was applied for classifying and selecting biodegradable active packaging produced using fish gelatin with the addition of palm oils and essential oils of cloves and oregano (da Silva e Silva et al., 2021). Additionally, AI- based data carrier technologies, such as RFID, are gaining prominence in smart food packaging and distribution (Hassoun, Abdullah, et al., 2022;

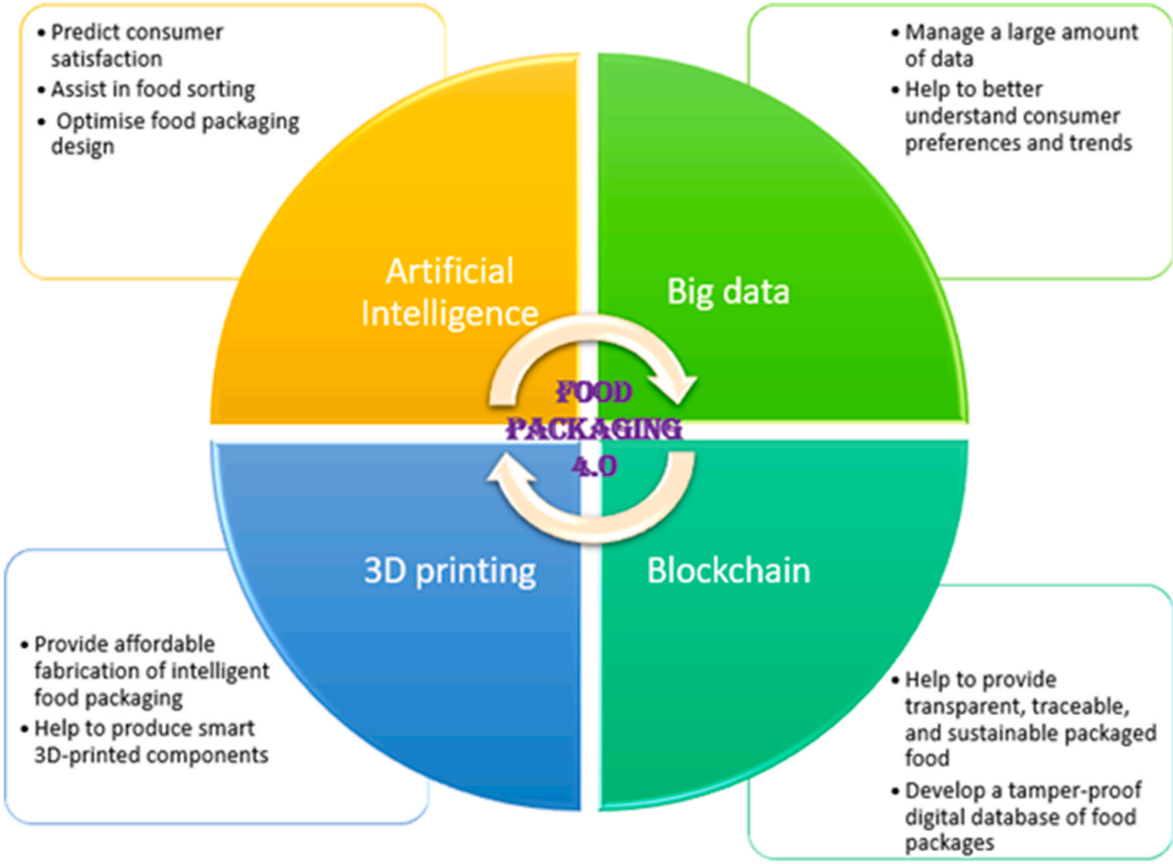

Fig. 6. Application of digital technologies to achieve the concept of "Food Packaging 4.0".

Mondal et al., 2019). Moreover, food sorting is another area of applications of AI in food packaging, especially when applied with other Industry 4.0 technologies, such as drones and robots (Echegaray et al., 2022).

5.3.2. *Role of big data*

Big data is another core element of Industry 4.0 that can be used to harness the power of massive amounts of data to improve food packaging and monitor various food quality parameters in real-time. Big data can be used to achieve an intelligent packaging design. For example, a user experience structure model based on social big data was used for children's food packaging design, providing children with interesting and creative emotional experience (Wen, Fan, Tao, & Gao, 2023). Another recent study used big data (124,077 Tweets) of Twitter discourse on zero waste concept, and found that the majority of popular tweets with zero waste hashtag (i.e., #zerowaste) refer to packaging and food packaging (Ganczewski & Jemielniak, 2022). The results showed a prevailing negative sentiment surrounding plastics as packaging material, while the sentiment was gradually more positive for paper, glass, and metal. Big data can help the packaging industry to understand consumer preferences and trends, fostering green design of food packaging (Rao & Li, 2023). Additionally, big data could enhance the ability of food packaging optimization and selection, allowing the selection of the best packaging methods for different foods (Tian & Song, 2020).

5.3.3. *Role of blockchain*

Several studies have reported the important role of blockchain in preventing and reducing food waste and loss. For example, in the meat industry, blockchain can be used to establish exactly when and where the meat is cut and packaged, leading to more accurate information between the various supply chain entities, which could result in improved inventory management, especially more accurate delivery times, and extended shelf-life of the product. The food supply chain and food packaging sector can benefit from the transparency provided by blockchain since this technology allows complex network stakeholders and operations to be connected, monitored and coordinated in a secure, transparent and decentralized manner (Tsolakis, Niedenzu, Simonetto, Dora, & Kumar, 2021). Blockchain architecture can be enabled by RFID sensors to develop a tamper-proof digital database of food packages, creating a transparent food supply chain (Mondal et al., 2019). In cold food supply chains, blockchain can promote transparency of temperature information (such as temperature abuse during storage and distribution) about food, thus maintaining the quality and safety of food products and supporting waste mitigation (Ndraha, Hsiao, Vlajic, Yang, & Lin, 2018).

5.3.4. *Role of 3D printing*

3D printing technology can be efficiently used to reduce and valorise food waste and provide affordable production of intelligent food packaging. It is possible to convert processing waste streams into edible novel foods or inedible biodegradable materials for food packing and other applications (Tracey, Predeina, Krivoshapkina, & Kumacheva, 2022; Yu & Wong, 2023). For example, a recent review paper reported that 3D-printed food packaging can be made from a wide range of food waste fractions, such as rice-husk fractions, sugarcane bagasse and banana peel, and marine waste (Yoha & Moses, 2023). In another publication, the potential of using 3D printing to produce multi-functional biomaterials from food waste was highlighted (Yu & Wong, 2023). A recent study reported that fruit waste such as banana peel can be converted into biodegradable food packaging casings using 3D printing technology (Nida, Moses, & Anandharamakrishnan, 2023). In another recent study, researchers reported the fabrication of eco-friendly composites from chitin and chitosan polymers extracted food waste, such as waste crab shell, using a 3D printing process (Mansingh et al., 2023). Results of mechanical, morphological, crystallographic, chemical composition, and thermal analysis suggested that the incorporation of these polymers into biopolymeric matrices (namely polylactic acid) could be a promising strategy for applications in food product packaging. In a similar study, an innovative green composite suitable for 3D printing applications was fabricated by producing anchovy fishbone powder and adding it to polylactic acid matrix (Scaffaro, Citarrella, Catania, & Settanni, 2022).

Additionally, 3D printing technology can be used to fabricate multifunctional smart 3D-printed components (e.g., sensors) that can be used for monitoring food quality, safety, and package integrity (Tracey et al., 2022). For example, a polylactic acid (PLA)-based temperature sensor was developed using 3D printing and incorporated in a smart cap for monitoring the integrity of liquid food packaging (Marasso et al., 2018).

6. Consumer acceptance of novel packaging solutions

In today's consumer era, acceptance of novel foods and technologies, and new product development, including emerging packaging solutions is of ultimate importance and should be thoroughly examined. It can be argued that the use of interactive packaging able to communicate shelf-life of the product to the consumer via the use of advanced technologies, such as IoT and blockchain, could be more effective in developing traceability and building trust than providing information about food processing steps to extend the shelf-life and/or the addition of preservatives or chemicals (Liegeard & Manning, 2020).

Increasing consumer attention towards novel foods and growing willingness to purchase safe, healthy, higher-quality, as well as innovative food products and packaging materials has changed the food industry over the last few years (Hassoun, Cropotova, et al., 2022). New packaging materials can meet consumer modern lifestyle and guide their choices towards the suitable storage method, level of food preparation (increasing consumption of ready-to-cook and ready-to-eat dishes), and communication of food safety/freshness information.

Herbes, Beuthner, and Ramme (2018) conducted a study to understand consumer behaviour towards different packaging materials in Western countries (in Germany, France, and the U.S). The results showed that consumers mostly focus on the end-of-life stage of packaging and prioritize recyclability and biodegradability over renewable origin. French and American consumers favoured recyclability, whereas the German consumers' perception was characterized by a strong presence of reusability. A recent study was conducted to investigate consumers' plastic packaging waste avoidance and recycling in private households in economically developed countries (Fogt Jacobsen et al., 2022). The results demonstrated that plastic packaging waste reduction depends on consumer motivation, ability, and opportunity, with environmental concerns and social norms being the main motivators for consumers to reduce plastic waste. The reasons found behind the acceptance of rejection of these packaging solutions ranged from practical utilitarian reasons through to hedonistic emotional and social reasons (Young, Mirosa, & Bremer, 2020). Regarding consumer acceptance of some new antimicrobial packaging techniques in China, only people with a high awareness of the risk associated with foodborne bacteria rated positively any new packaging solutions that can control such microorganisms, while the rest of the respondents seemed disinterested (Wang, Mirosa, Hou, & Bremer, 2022). Consumers in the United States revealed that respondents are willing to pay a price premium for food made with new compared with conventional technology (Grant et al., 2021). Therefore, depending on the geographical location, dietary habits, and level of education, consumers may not constantly evaluate food products based on their safety attributes, but they may prioritize the price and convenience of the packaging.

From a legislative perspective, a new regulation was recently established to ensure that recycled plastic can be safely used in food packaging. However, this goal remains controversial in other regions, such as Asia, where daily life relies heavily on large quantities of plastic packaging and single-use plastics. A recent study indicated that in Brazil, China, Poland, Portugal, Ukraine, and the USA, most respondents are only willing to pay up to 10% more for new packaging (Kochanska et al., 2022). Consumer acceptance of nanotechnology and other novel food technologies has been reviewed by Siegrist and Hartmann (2020) identifying some knowledge gaps that future research should address.

7. Future directions and conclusions

Food waste is a global burden with nearly one-third of all food produced lost or wasted, whereas overuse of plastics is becoming a great concern in today's society. The food industry is one of the most affected sectors by these two dilemmas (i.e., food waste and plastic), and food packaging is an integral part of the food chain that significantly contributes to these challenges. Indeed, traditional food packaging materials based on petroleum, such as polypropylene, polyethylene, and polystyrene are often disposable and could generate a large amount of waste, which usually ends up in landfills or the ocean, polluting the environment. Furthermore, producing these materials also has other significant environmental impacts related to use of many natural resources and energy. Therefore, creating sustainable alternative food packaging solutions that reduce waste and minimize environmental impact has become essential. Promising initiatives have been launched to develop more eco-friendly food product packaging, such as compostable packaging, reusable packaging, and packaging made from natural materials and nanoparticles, using advanced technologies and alternative approaches.

The present review focuses on the potential of digital and other Industry 4.0 technologies in reducing food waste and decreasing the use of plastic and other non-biodegradable materials, Alternatives to conventional packaging solutions offer many desired features, such as extending shelf-life and increasing safety, and untimely enhancing food sustainability. Industry 4.0 innovations offer exciting opportunities to improve production processes' efficiency and enhance food safety, quality, and traceability.

Emerging technologies, such as nanobiotechnology, IoT, AI, big data, smart sensors, blockchain, and 3D printing can provide promising solutions to optimize the fabrication of smart packaging, and reduce food waste, creating more sustainable and efficient food production systems. For example, IoT and smart sensors can monitor food storage and transportation conditions and determine food freshness and other quality parameters, which can help prevent or at least reduce food loss and waste. AI can analyse sensor data and predict consumption trends, enabling producers to produce optimal amounts of food and minimize excess. Big data can also be of great assistance to understand consumer preferences and improve food packaging design. Blockchain has the potential to provide efficient packaging traceability to food supply chain, whereas 3D printing could give new insights into many applications in food product packaging. Regarding nanobiotechnology, it could help turning food waste into valuable nanomaterials and other structural components that could present valuable opportunities to smart food packaging, especially when combined with recent development in nanosensors and nano-enabled sensing solutions.

Harnessing the power of Industry 4.0 technologies in the food packaging sector can reduce the amount of waste generated along the food supply chain while simultaneously preserving natural resources and minimizing environmental impact. However, the application of Industry 4.0 technologies in the food packaging sector is still in its infancy, with much potential yet to be explored. High cost remains one of the main obstacles to increasing the use of smart food packaging solutions enhanced by Industry 4.0 innovations. Indeed, a recent study reported that the cost of such innovative packaging strategies could be 10 to 50 times greater as compared to petroleum-plastic packaging (Perveen et al., 2023). Technophobia and resistance to change (*silo mentality*) could be highlighted as another barrier facing more widespread adoption of active and intelligent packaging enabled by Industry 4.0 technologies. Moreover, dependency on plastic materials in packaging could make it difficult for consumers to adopt alternative solutions. Additionally, inconsistent public policies and regulations about the implementation of Industry 4.0 technologies among different countries could be considered as an additional drawback to more implementation of these advanced technologies.

Implementation of suitable collaborative innovation approaches and multi-actor collaboration (involving food waste producers, food packaging manufacturers, food technologists, in addition to academic scientists, researchers, and other scholars) should be prioritized to accelerate the adoption of "Food Packaging 4.0" concept, being a holistic and integrated framework for achieving green sustainable packaging as an essential step toward reaching circular economy objectives and fostering sustainable development goals. Moreover, more investment in educating consumers about the benefits of innovative technologies and the importance of adopting alternative solutions to plastic is essential for achieving zero food waste and zero plastic waste goals. As the implication of Industry 4.0 digital platforms in the food packaging sector continues to increase, it is expected that the potential for improved efficiency, cost savings, and more sustainable use is only going to grow in the near future, turning concepts into reality.

Declaration of competing interest

No conflicts of interest are declared for any of the authors.

CRediT authorship contribution statement

Abdo Hassoun: Conceptualization, Writing – original draft, Writing – review & editing, Supervision. **Fatma Boukid:** Writing – original draft. **Fatih Ozogul:** Writing – original draft. **Abderrahmane Aït-Kaddour:** Writing – original draft. **Jose Miguel Soriano:** Writing – original draft. **José M. Lorenzo:** Writing – original draft. **Rosa Perestrelo:** Writing – original draft. **Charis M. Galanakis:** Writing – original draft. **Gioacchino Bono:** Writing – original draft. **Abdelhakim Bouyahya:** Writing – original draft. **Zuhaib Bhat:** Writing – original draft. **Slim Smaoui:** Writing – original draft. **Anet Režek Jambrak:** Writing – original draft. **José S. Câmara:** Writing – original draft, Writing – review & editing.

Data availability

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