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REVIEW ARTICLE

From traditional packaging to smart bio-packaging for food safety: a review

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Abstract
The need to urgently find alternative plant-based biodegradable fibres is not just important, it is a pressing necessity. The severe environmental damage caused by plastic packaging materials demands immediate action. It is a responsibility that everybody should share to reduce the global plastic pollution rate and environmental footprint. Biodegradable films from natural and waste products have gained considerable consideration for their ability to guarantee optimal product conservation while avoiding any risk of contamination or intoxication. Therefore, this overview addresses recent developments in food packaging and the application of sensors to indicate possible packed food spoilage. The new role of food packaging was discussed widely, from traditional to bio-based, active and intelligent packaging. Until a few years ago, food packaging had the sole purpose of protecting food from external contamination. However, the barrier effect is no longer enough: the packaging should act directly on the food and the surrounding space. The interesting innovation that responds to this need is active and intelligent packaging, a market with solid growth in recent years. It allows the enhancement of food conservation and the detection of pathogens while maintaining good monitoring of the environment inside the package, continuously recording the food conditions. This more complete and interactive information is recorded thanks to special analytical devices: sensors. They can detect and transmit a message to the consumer about food quality, freshness and safety, thanks to the ability to record internal and external changes in the product's environment. However, these devices are not free from limitations, such as costs and performance, which limit their wider use.

Keywords Bioplastics · Food packaging · Smart packaging · Bio-based sensors

Introduction

The alarming accumulation of plastic debris in the North Pacific Ocean, an area twice the size of Texas, serves as a stark reminder of the urgent need for sustainable alternatives to plastic packaging. This pollution, which harms marine life through ingestion and entanglement, is just one of the many problems caused by plastic. Microplastics, ingested by marine organisms, enter the food chain and potentially affect human health. A recent study estimated that humans consume tens of thousands of microplastic particles annually (Zhao and You 2024). The pollution caused by plastic is not only marine. While beneficial for crop yields, agricultural plastic mulch can contaminate soil when plastic fragments break down. These fragments can affect soil organisms and overall soil health. Indeed, plastic residues can persist in the soil, affecting its long-term productivity. They degrade into microplastics, thus contaminating the soil and affecting its health and fertility. These are just some of the many problems caused by plastic packaging, underscoring the urgent need for more sustainable alternatives and better waste management practices.

The potential of bioplastics to significantly reduce environmental impact and provide a sustainable alternative to commercial plastic is a beacon of hope in the field of food packaging. Bioplastics, produced from renewable resources such as corn starch, sugar cane, and cellulose, reduce dependence on fossil oil and the overall carbon footprint. This potential of bioplastics to revolutionize the food

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packaging industry is a promising step towards a more sustainable future.

Until a few years ago, the traditional goals of packaging have been to protect the food product from external biochemical contamination and to provide consumers with ease of use during the storage, transport and delivery phases (De Paola et al. 2022; Moustafa et al. 2019). Therefore, packaging was characterized by a series of characteristics that denote a particular propensity for passive action. However, a trend of recent decades is to innovate this perspective and offer generic protection of the product, making them functional and interacting with consumers. As consumer concerns about food safety and product freshness increased, packaging was needed to monitor and communicate food status. Additionally, government regulations regarding food safety and preservation have pushed the industry to seek more advanced solutions to ensure food quality. The challenge of recent years is to extend the food shelf-life over time by controlling chemical, microbiological, enzymatic, chemical-physical, and mechanical phenomena.

Technology, which has become increasingly sophisticated over the past years, has the merit of simplifying and significantly improving our lives. It plays a fundamental and, in some cases, indispensable role in our daily lives and is constantly evolving today. It is also increasingly established in the packaging in the food and industrial sectors, with the creation of increasingly innovative products, referred to as "functional packaging" (Biji et al. 2015).

Functional packaging falls into the packaging systems capable of constantly monitoring various parameters closely correlated with the variation in food storage conditions. These systems can acquire and transmit information about foods in real time without altering their nutritional properties, shapes, or colours. This process can take place thanks to the creation of particular, specific devices and highly technological indicators external or internal to the package, which allow continuous feedback on the state of the food to be provided, improving the shelf life and quality of the food.

In particular, intelligent packaging provides information to the consumer through barcode labels, gas indicators to detect or record changes external or internal to the packaging, temperature indicators, or biosensors. Moreover, developments concerning delayed microbial growth within packaging, delayed food oxidation, and slower moisture migration in dried products have led to several advances in the active packaging field (Alessandroni et al. 2022; Ouahioune et al. 2022). Smart packaging comprises both active and intelligent packaging systems to provide more accurate information about the food product conditions to the consumer and display a protective effect over the food product through, e.g., antioxidant and antimicrobial agents (Rodrigues et al. 2021).

This overview addresses the most critical smart packaging systems and their different applications. Bio-packaging and smart packaging exploitation have been widely investigated and reviewed in past years. However, to our knowledge, a comprehensive overview covering all the aspects of novel food packaging, from the introduction of bioplastics to the innovation of active and intelligent packaging, is very rare. Table 1 summarizes the most relevant review papers published about innovative food packaging since 2018 to elaborate on the originality of the current overview.

Table 1 Summary of review papers about improved food packaging and main topics discussed

References	Edible/bio-packaging	Active packaging	Intelligent packaging
Bayram et al. (2021); Chen et al. (2019); Coppola et al. (2021); Hassan et al. (2018); Huang et al. (2019); Kumar et al. (2022); Liu et al. (2021); Mangaraj et al. (2019); Matheus et al. (2023); Mohamed et al. (2020); Nilsen-Nygaard et al. (2021); Parreidt et al. (2018); Taherimehr et al. (2021); Zhao et al. (2020)	✓	X	X
(Asgher et al. (2020); Atta et al. (2022a); Bahrami et al. (2020); Chawla et al. (2021); Guo et al. (2023); Huang et al. (2019); Rangaraj et al. (2021); Omerović et al. (2021); Shao et al. (2021); Sharma et al. (2021); Vilela et al. (2018); Yildirim et al. (2018)	X	✓	X
(Asgher et al. (2020); Atta et al. (2022a); Rangaraj et al. (2021); Trajkovska Petkoska et al. (2021)	✓	✓	X
(Cheng et al. (2022); Dodero et al. (2021); Halonen et al. (2020); Kalpana et al. (2019); Khan et al. (2024); Konala and Gaikwad (2021); Osmólska et al. (2022); Ozcan (2020); Priyadarshi et al. (2021); Rodrigues et al. (2021); Weston et al. (2021); Yousefi et al. (2019)	X	X	✓
(Drago et al. (2020); Han et al. (2018); Majid et al. (2018); Mustafa and Andreescu (2018); Soltani Firouz et al. (2021)	X	✓	✓
Present overview	✓	✓	✓

The bioplastics

Bioplastics have been proposed as a potential solution to mitigate environmental damage, particularly in the single-use food packaging sector.

General concepts

Bioplastic refers to a category of plastic materials derived from renewable biological resources, aiming to reduce environmental impact compared to conventional plastics. Furthermore, bioplastics can improve the image and reputation of companies that adopt more sustainable practices, responding to growing consumer expectations for greener products and packaging. The properties of bioplastics can vary significantly based on their composition and manufacturing process. Some may be better suited for specific applications than others. However, it is essential to note that not all bioplastics are created equally (Ali et al. 2023; Tennakoon et al. 2023; Zhao et al. 2023). Some bioplastics may require specific composting conditions to degrade fully, while others may not be compostable but only biodegradable. Furthermore, the production process and disposal of bioplastics must be managed correctly to maximize environmental benefits and minimize negative impacts. The following subchapters will discuss these aspects in detail.

Compostable and biodegradable materials: eco-friendly solutions for modern industry

The applications of bio-packaging fall within the strategic plan for the circular economy (Gan and Chow 2018), by promoting waste disposal using compostable and biodegradable materials (Fig. 1).

Compostability and biodegradability are distinct properties, even if they are often mistakenly used as synonyms. The distinction between biodegradable and compostable materials is crucial to understanding each type's practical implications and environmental benefits.

A compostable product can be disposed of with organic waste and recovered in composting plants. Through the composting process, it is then transformed into a new material, giving it a new life and giving it the name of "compost". Compost is an odourless organic substance and is often reused as a fertilizer. This sector's most used compostable materials are BPS (Biodegradable Plastics from Starch), used for food packaging and bags, and PHA (polyhydroxyalkanoates). The latter are polymers produced by microorganisms, used for films and food containers, and compostable in domestic and industrial environments.

Fig. 1 The environmental advantages of using bio-packaging

Compostable materials require adequate infrastructure for industrial or home composting. The absence of such structures can limit the effectiveness of composting.

A biodegradable product is defined as one that can degrade through processes naturally generated by microorganisms such as fungi and bacteria. This mechanism, activated automatically, ends without human help and avoids contaminating the surrounding environment. Among the most used biodegradable materials in the food packaging sector, we find PLA (polylactic acid), used to produce bottles, cutlery, and food packaging. Decomposable under specific industrial composting conditions. Biodegradable materials do not always decompose quickly in landfills or natural environments. They may require specific temperature and humidity conditions to degrade effectively. For example, in the case of PLA, high temperatures (around 55–60 °C) are necessary for industrial composting. These high temperatures accelerate the decomposition of the material relatively quickly.

Therefore, bioplastics have one or both characteristics and can originate from renewable sources (e.g., vegetable or animal origin) and fossils (e.g. oil). Bio-based films are specially designed for food packaging and are relatively less harmful to the environment (Terzioğlu et al. 2021; Yaradoddi et al. 2022).

Renewable natural resources of edible films

There is an ever-greater desire to develop edible packaging and films from renewable sources that can improve the quality and extend the shelf-life of the products contained therein (Claudia Leites et al. 2021). Edible films are made using edible biopolymers as a base. The biopolymers used for this purpose can be polysaccharides, lipids, and proteins (Teixeira et al. 2014). Additives such as plasticizers are added to biopolymers and mixed with the basic biopolymers to alter some of the most critical physical properties of the films obtained. Packaging, being in contact with food, represents an ingredient of the food itself. For this reason, it is necessary to use compounds appropriate to the application (Min and Krochta 2005).

Biopolymers constitute a large family of materials, and based on their numerous sources, applications and different preparation techniques, they can be divided into three main groups (Fig. 2).

Polysaccharides such as cellulose, starch and chitosan are among the most used materials for creating edible films intended for food preservation. These natural materials offer numerous benefits in terms of sustainability, food safety, and functionality.

Cellulose is the most abundant polysaccharide present in nature, derived mainly from plants. Cellulose-based films are transparent and durable and can form an effective barrier against oxygen, moisture and microorganisms, helping to extend the shelf life of foods. Pereira et al. have created a thermally stable membrane based on acetylated banana pseudostem cellulose (Pereira et al. 2022). This membrane could inhibit the growth of *Staphylococcus aureus* and *Escherichia coli* on its surface, confirming the potential use of these membranes as bio-packaging for food preservation. Starch, obtained from sources such as corn, potatoes and rice, is also widely used in producing edible films due to its biodegradability and ease of processing. Starch films can be improved by adding plasticizers and other additives to achieve optimal mechanical and barrier properties, thus maintaining food freshness. Bajer et al. have verified the potential application in the food industry for edible films based on potato starch, chitosan and aloe vera gel, obtaining a new intelligent material with antimicrobial and antioxidant properties that are necessary for food packaging (Bajer et al. 2020).

Finally, chitosan, derived from the chitin in crustacean shells, has excellent antimicrobial and antifungal properties, making it ideal for applications in food packaging. Chitosan films can inhibit the growth of bacteria and mould, extending the shelf life of foods and improving food safety. Additionally, chitosan is biodegradable and biocompatible, making it a sustainable choice. About this, Diaz-Montes et al. have developed sustainable films using a chitosan-based blend for mushroom preservation. They demonstrated that applying dextran/chitosan blend films may be viable as a bio-packaging alternative for preserving fresh mushrooms, extending their shelf life and quality (Díaz-Montes et al. 2021).

Manufacturing techniques such as heating, drying, and enzymatic action should be appropriate to obtain an edible coating for food-grade products. Controlling the conditions of the manufacturing process is significant, as any change in the treatment conditions can alter the reaction kinetics and mechanisms.

The advantages of using biopolymers are innumerable; the most important is their much shorter total degradation than conventional plastic, which contributes to a less polluted ecosystem. However, bio-based plastics are not without some disadvantages. They present some limitations in processing, and a sore point is their production cost, which has limited the growth of this sector. Additionally, some bioplastics are only compostable in industrial composting facilities and are not always available everywhere, limiting their environmental benefit.

Potential applications of edible films in food

Edible films and coatings can be ingested with the product in the packaging and can, therefore, be considered food in all respects. The main objective of these films is to improve and prolong the quality of the food by limiting the transfer of gas, humidity and any fats inside the food (Gupta et al. 2022). Furthermore, packaging for food use must boast various

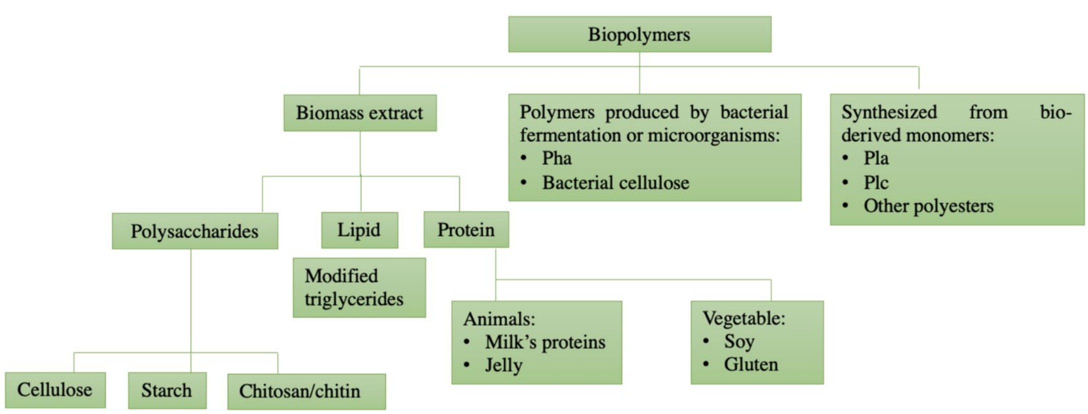

Fig. 2 Classification of biopolymers based on their origin: biomass extract, microbial production, or chemical synthesis

characteristics, such as excellent mechanical properties, thermal stability and good organoleptic characteristics.

An edible film is a thin layer of material made up of edible components. The main advantages that distinguish these structures are their biodegradability, biocompatibility, and minimal toxicity properties (Alkan and Yemenicioğlu 2016) (Fig. 3).

An edible film is classified according to the structural materials used. For this purpose, components of proteins, polysaccharides, and lipids are used. These substances are added to plasticizing agents (glycerol, fatty acids, sorbitol, and glucose), solvents, and various preservative additives. These preservative additives play a crucial role in extending the shelf life of the food product by inhibiting the growth of microorganisms and preventing spoilage. The only solvents available are water and ethanol solutions to maintain the edibility characteristic.

There are proteins among the most used polymers for forming films. These are macromolecules with very specific amino acid sequences and, therefore, concrete molecular structures. Proteins are the most used resources compared to other film-forming resources thanks to the characteristics they enjoy. In fact, secondary to quaternary protein structures can easily undergo modifications to achieve the desired film properties by thermal denaturation, application of pressure and irradiation, and mechanical treatments. Such modifications and applications can adjust products' most crucial physical properties, such as mechanical properties and thermal stability. The primary protein sources used for film-forming techniques are derived from a broad spectrum of plant and animal sources, including animal tissue, eggs, cereals, milk and dairy products. Plant-based proteins and polysaccharides have attracted global industry interest. In particular, edible films produced from pea protein and pea starch have been found to have excellent mechanical properties, water vapour permeability, transparency and solubility. In this regard, Farshi et al. demonstrated that pea-based edible films preserve food quality, maintain vegetable texture and nutritional content, prevent nuts from rancidity, improve fruit freshness, and package dual-textured foods (Farshi et al. 2024).

Milk proteins, such as casein or whey proteins, are a potential sustainable source of biopolymer derivatives (Chaudhary et al. 2022; Kandasamy et al. 2021). Due to their various benefits, they have shown great promise in replacing plastics in different applications. Besides nutritional benefits, casein and whey proteins have versatile physico-mechanical properties such as solubility and biodegradability, making them ideal for developing several innovative new edible food packaging systems (Daniloski et al. 2021). These commercial films are also antimicrobial, shielding foods against physical and microbial contamination. This critical property extends the shelf life of the food product.

The most relevant trends can be identified following the latest advanced studies conducted:

- The versatility of edible films is evident in the diverse materials used for food coatings, including starches,

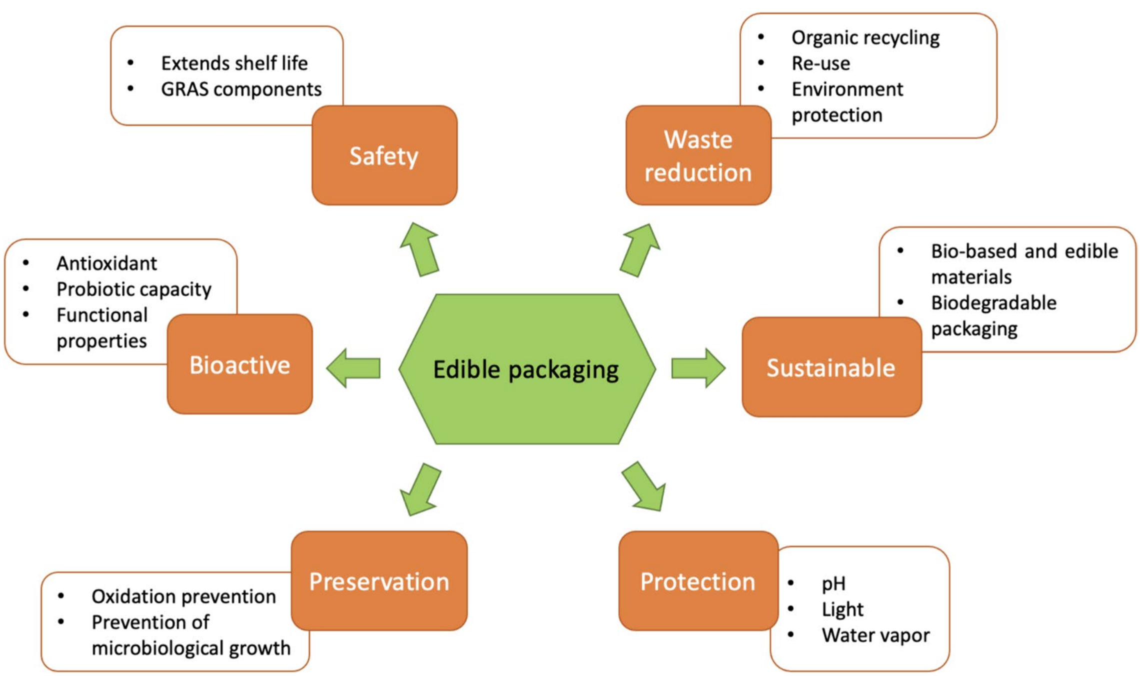

Fig. 3 Advantages of edible packaging in food applications

soy proteins, waxes, chitosan, and whey. Recent studies have even explored the use of polymeric materials for edible film formulation, opening up a world of possibilities for food packaging.
- Numerous studies have underscored the protective role of edible films in preserving the quality and extending the shelf life of various food products. This reassures us about the safety and quality of the food we consume.
- The future of food packaging is bright, with numerous ongoing research projects harnessing the potential of edible films as carriers for bioactive compounds and nanoparticles. This research not only instils optimism about the future of food packaging but also underscores the significant role of these innovative technologies in shaping the industry (Falguera et al. 2011).

Regulatory aspects of edible films are crucial to ensuring consumer safety and promoting confidence in new food packaging materials. A rigorous and transparent regulatory framework, close surveillance, continuous research, and innovation are essential for the widespread adoption of these products. Regulations must balance food safety, sustainability and promoting innovation, ensuring that edible films can deliver their benefits safely and effectively (Koirala et al. 2023; Pei et al. 2024). The main regulatory aspects related to edible films are

- Food safety. This is the most critical aspect of the regulation of edible films. The materials of which the bio packaging is made come into contact with the food; for this reason, it must comply with rigorous standards that guarantee the absence of risks to human health (Roy et al. 2023).
- Authorized ingredients. The regulations specify which substances can be used and in what quantities. In the United States, for example, ingredients must be recognized as Generally Recognized as Safe (GRAS). At the same time, they must be included in the positive lists of authorized food additives in Europe.
- Labeling and consumer information. Labeling is another crucial aspect. Edible film manufacturers must provide clear and complete information on the product, including ingredients, instructions for use, and any nutritional claims.
- Production and hygiene standards. Another essential aspect that should not be underestimated is ensuring the products are safe, high-quality, and contaminant-free. Regular tests are necessary throughout the production process to ensure compliance with safety standards.
- Innovation and sustainability. Finally, regulations are evolving to keep pace with innovations in the food packaging industry and the growing focus on sustainability, which has been discussed extensively in the previous subsections.

Adopting all these measures has made it possible to develop greater environmental awareness on the part of consumers. Consumers are increasingly concerned about the environmental impact of plastic waste and are more likely to choose biopackaging if they are informed about the environmental benefits of biopackaging. The biggest limit remains the cost. It is a significant factor in the acceptance of biopackaging. Often, biodegradable materials are more expensive than traditional plastics. Many consumers are willing to pay a higher price for eco-friendly products, but this willingness can vary based on income and environmental sensitivity (Guo et al. 2024; Sonck-Rautio et al. 2024; Zhang et al. 2024).

The food packaging

From traditional to smart food packaging

Food packaging is increasingly important in modern society to preserve food quality and safety regarding smart delivery of nutrients, improvement of nutritional value, consistency and texture, and protection of aroma, flavour and other ingredients (Primožič et al. 2021). While non-biodegradable plastic polymers are commonly used in food packaging, they pose significant risks to human health and the environment. In contrast, biopolymers, derived from abundant natural sources such as plants, food and agricultural wastes, offer a sustainable and safe alternative. These biopolymers, based on polysaccharides like starch, cellulose, alginates, gums, pectins, and chitin/chitosan, or lipids like beeswax, carnauba wax, oils, and free fatty acids, are not only environmentally friendly but also provide the necessary properties for adequate food packaging (De Paola et al. 2021a, b, 2022; Liu et al. 2021; Matheus et al. 2023; Parreidt et al. 2018), proteins (gluten, soy proteins, zein, casein, whey, gelatin, collagen) (Chen et al. 2019) or lipids (beeswax, carnauba wax, oils, free fatty acids) (Atta et al. 2022a). Biopolymers, with their mechanical, thermal, wetting, sensory, barrier, and water vapour permeability properties, find various applications in food preservation. They are particularly suitable for packaging fruits, vegetables, cheese, meats, poultry, and seafood, effectively extending the shelf-life and maintaining the safety and quality of these food products. These biopolymers can be either derived from natural sources or synthesized from bioderived monomers or produced directly from microorganisms, offering a versatile and sustainable solution for food packaging needs (Azeredo et al. 2019; Cazón and Vázquez 2021; Mangaraj et al. 2019; Nilsen-Nygaard et al. 2021). Therefore, new packaging materials and their application technologies have recently been developed for food packaging. Edible coatings and nanocomposites are emergent biomaterials that extend the shelf-life, safety and quality of food during its life cycle (Kumar et al. 2021). Smart food packaging is emerging as a novel technology capable of enhancing and monitoring the quality and safety of food during its shelf life. It comprises active and intelligent packaging systems to provide more accurate information about the conditions of food products to the consumer. Also, it displays a protective effect over the food product through the use of, e.g., antioxidant and antimicrobial agents (Rodrigues et al. 2021).

Active food packaging

The demand for convenient, transparent and more sustainable packaging has led to developing new packaging technologies, such as improved packaging. These innovative solutions, including active food packaging that incorporates active agents into packaging materials, are crucial in enhancing food safety, stability, functionality and shelf-life, reassuring consumers (Yildirim et al. 2018). Typical active packaging systems include antimicrobial packaging, antioxidant packaging, carbon dioxide emitters, moisture absorbers, ethylene absorbers, and freshness indicators (Guo et al. 2023), as summarized in Fig. 4.

For instance, antimicrobial packaging is based on the addition of antimicrobial agents—such as essential oils, plant extracts, chitosan, enzymes, bacteriocin, and inorganic nanoparticles—into films to suppress the growth of pathogenic microorganisms and limit or avoid food contamination (Chawla et al. 2021; Ju et al. 2019; Sharma et al. 2021; Sung et al. 2013). Antioxidant active food packaging is an alternative to more traditional strategies (such as direct addition of antioxidant compounds and modified atmosphere) to limit lipid oxidation and consequent loss of sensory and nutritional food quality (Gómez-Estaca et al. 2014; Sharma et al. 2021).

Bio-composite films based on hydrocolloids as biopolymers, clays as reinforcement agents, natural antimicrobials, and antioxidants are effective active biodegradable packaging materials. (Pinto et al. 2021). Gelatin-based films can be used as active and smart edible films thanks to their good mechanical and barrier properties, biodegradability, low production cost, and compatibility with incorporating antimicrobial and antioxidant agents (Said et al. 2023). The addition of essential oils, phenolics and other fruit extracts to chitosan-based films effectively improves their mechanical, barrier, antimicrobial and antioxidant properties (Flórez et al. 2022; Wang et al. 2018). Cellulose derivatives—including cellulose acetate, cellulose sulfate, cellulose nitrate, methylcellulose, ethyl cellulose, carboxymethyl cellulose, and nanocellulose—were extensively investigated (Atta et al. 2021a, b, 2022b; Liu et al. 2021). They can be carriers of several food additives, antimicrobial agents and antioxidants (de Souza et al. 2018). In addition, active (antioxidant and antimicrobial) protein-based materials guarantee food safety and prolong the food

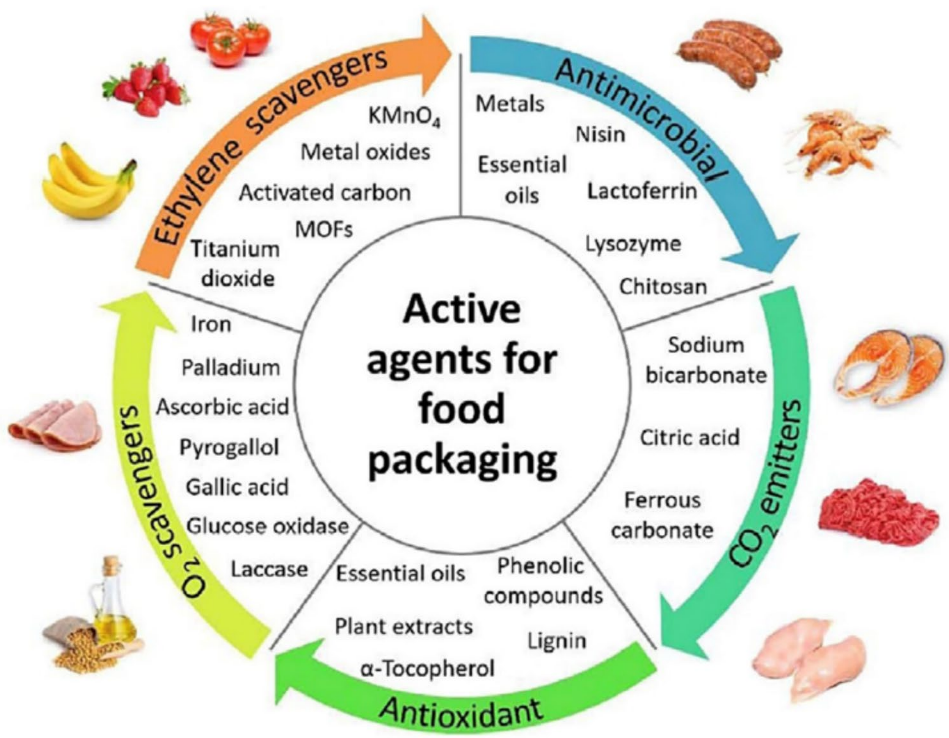

Fig. 4 Active agents for different active food packaging applications (Vilela et al. 2018)

shelf life by inhibiting or delaying microorganism growth and lipid oxidation (Chen et al. 2019).

Nanotechnology has significantly impacted science and technology, and its potential in food packaging is increasingly being explored. Chitosan and cellulose, which have been extensively used in bioplastics production, are now being investigated as nanoparticles to reinforce the structure and enhance the antimicrobial properties of biocomposites. This exploration of nanotechnology in food packaging opens up a world of possibilities and will intrigue the audience (Garavand et al. 2022; Vilarinho et al. 2018). Bio-nanocomposites are bio-based polymers composed of a biopolymer acting as a matrix and a nanoparticle or nano-fibre added as a reinforcement agent to improve thermal and mechanical properties, flexibility, gas barrier characteristics, biocompatibility, biodegradability, eco-friendliness, and cost-effectiveness (Atta et al. 2022a; Chawla et al. 2021; Sharma et al. 2020; Youssef and El-Sayed 2018). Various nanostructures can provide active properties to food packaging systems, such as nanoparticles, nanoplatelets, nanotubes, nanofibers and nanowires (Youssef and El-Sayed 2018). The most investigated bio-nanocomposites for food packaging applications derive from starch and cellulose, PLA, PHB, polycaprolactone (PCL) and poly-(butylene succinate) (PBS). Metal (mostly Ag) and metal oxide (mostly ZnO and TiO_2) nanoparticles are widely used to functionalize polymeric materials and obtain innovative food packaging for their thermal stability, antimicrobial, optical and catalytic properties (Rhim et al. 2013). The most promising nanoscale fillers are layered silicate nanoclays such as montmorillonite and kaolinite. Melanin nanoparticles are other functional materials that improve the characteristics of nanocomposites thanks to their properties of photosensitivity, light barrier action, free radical scavenging, and antioxidant activity (Roy and Rhim 2022). Moreover, inorganic and metal nanoparticles allow to reduce the use of preservatives and inhibit the microbial growth (Hoseinnejad et al. 2018). Emergent technology is the nano-encapsulation of anti-microbial compounds by nano-carriers (Bahrami et al. 2020).

Potential health effects and safety aspects of active food packaging systems

Edible films and coatings for food packaging are mainly polysaccharides, lipids or proteins, with no negative impact on human health. Among them, nano-based food packaging has several advantages over traditional packaging (Sharma et al. 2017). Nevertheless, the overall effects of nanomaterial on human health and environmental safety are still not entirely known. The safety of metal and inorganic nanoparticles in food packaging needs more research and clinical trials before their commercialization. Indeed, the direct contact between food and nanocomposites makes the migration of nanoparticles from packaging materials into food possible, but few studies have focused on this topic. The nanoparticle toxicity increases as particle sizes decrease (Nile et al. 2020). Moreover, nanoparticles are highly reactive in contact with biological components (Pereda et al. 2019), and their specific biokinetics could favour their migration from packaging materials to food. It is not fully understood if nanoparticles can enter and accumulate in the human body, causing cytotoxicity, genotoxicity, apoptosis, necrosis, and breakage of DNA strands (Khanna et al. 2015). In addition, the behaviour of nanoparticles in the environment depends not only on the physical and chemical character of the nanomaterial and their concentration but also on the characteristics of the receiving environment (Silvestre et al. 2011). Due to their small sizes, nanoparticles can be released into air, soil and water. Therefore, the toxicological effect of nano-based materials on environmental ecosystems needs more investigation (de Azeredo et al. 2018; dos Santos et al. 2020). Therefore, the risk assessment requires further research and detailed analysis before its application (Huang et al. 2015; Sufian et al. 2017).

In addition, other active reagents can be released into food products, affecting their colour, flavour and toxicity.

Intelligent food packaging

For the food industry, it is essential to guarantee high levels of quality and safety. Therefore, it is necessary to have technologies capable of ensuring precision and sensitivity at the service of product quality, detecting the presence of any chemical or biological contaminants quickly and reliably. This technology uses indicators and sensors applied to the packaging and provides important information on any alterations to the food and the degree of freshness of the packaged product. Despite this, the sensors most in use are made with synthetic materials, which harm the environment and the habitat of fauna and flora. Industries and consumers are increasingly characterized by a growing level of awareness, especially concerning environmental protection and food waste reduction. Therefore, as with food packaging, the application of bio-based materials as indicators and sensors is also emerging.

Classification and application of bio-based sensors

Intelligent food packaging performs a remarkable task for food preservation; it must increase and maintain the shelf life of packaged foods by detecting any changes in the conditions of the foods (Sobhan et al. 2021). The latest studies have highlighted the development of various bio-based sensors and indicators, such as temperature integrators (TTIs),

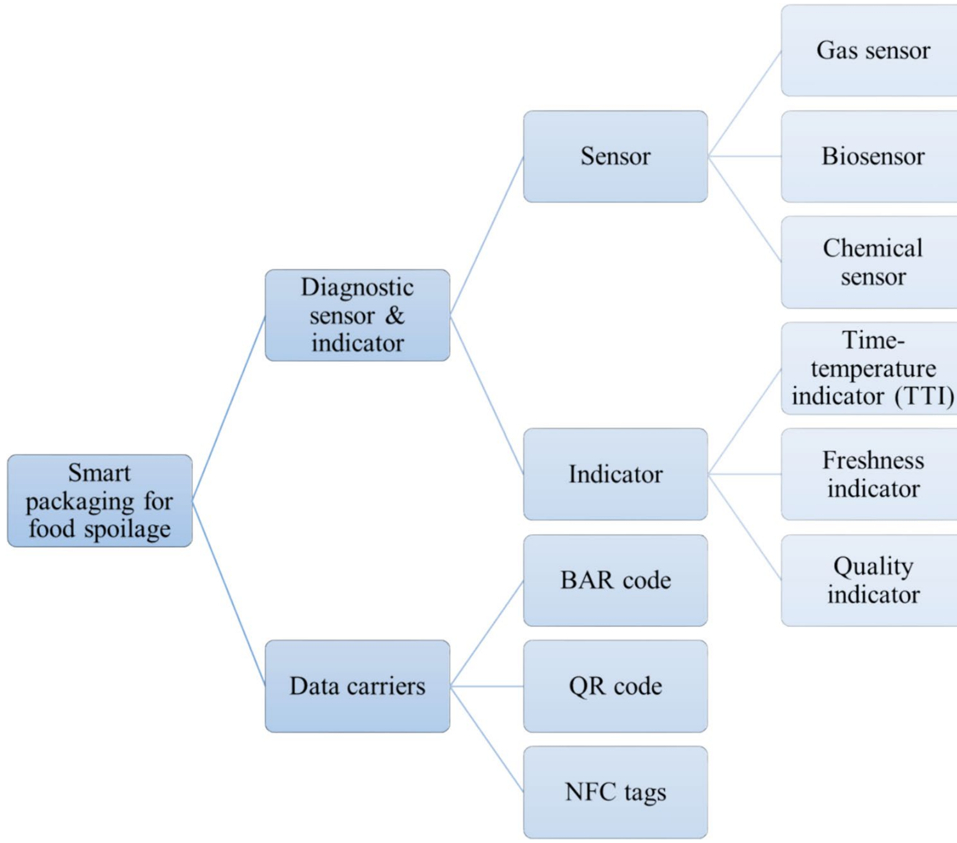

Fig. 5 Classification of smart devices used for food spoilage detection and monitoring in innovative packaging

freshness indicators, pathogen biosensors, etc., with promising results (Fig. 5).

A bio-based sensor used for food packaging must allow real-time monitoring of any degradation of the packaged food.

Some of the most used bio-based sensors in food packaging are mentioned and described below.

Gas sensors

Suppose the expiry date written on the packaging provides fundamental information on the shelf life of the food. In that case, the gas sensor can detect and signal any premature rancidity of the packaged food. These sensors are suitable for monitoring the quality and safety of food by detecting and tracking the presence of spoilage gases, such as CO_2 or oxygen (Park et al. 2015). The operating principle is simple. Generally, sensors are composed of a receptor (whose function is to transform physical or chemical information into a form of energy) and a transmitter (which converts the energy into an analytical, optical, electrical, or thermal chemical signal). Carbon dioxide sensors are one of the most used gas sensors to determine the level of CO_2 inside food packaging. It is primarily used for perishable foods, mainly fish and meat; it can be inserted into the package and checked with the naked eye (Osmólska et al. 2022). Ammonia, a crucial indicator in the meat decomposition process, is commonly used to evaluate the freshness of meat. Zhou et al. have developed a reliable ammonia sensor based on Polyaniline/CuTsPc/AgNPs. Their research has shown that the PANI/CuTsPc/AgNPs flexible gas sensor boasts a rapid response time (61 s), a quick recovery time (19 s), a low theoretical detection limit (0.234 ppm), a high response rate (3.6 towards 500 ppm NH_3), and excellent stability at room temperature. This system, with its real-time detection and monitoring capabilities, offers a dependable solution for the food packaging industry, making it a highly promising tool for future applications in smart packaging (Zhou et al. 2024).

Bio-based sensors for food freshness

Food spoilage has become a significant problem and is currently one of the most pressing concerns as it is risky to health. The most important quality to measure to ensure food safety is its freshness (Faradilla et al. 2021; Felicia et al. 2023). The freshness of food can be detected with the help of some biosensors suitable for the purpose. These bio-based sensors are sensitive, observable with the naked eye, and measurable through electronic devices. They are designed for fresh foods, such as fruit and vegetables that have been recently harvested and processed, and poultry, meat, and dairy products that have been recently processed or slaughtered (Dirpan et al. 2023).

In previous studies, several biosensors have been used to determine the freshness of foods; they may be able to detect changes in pH, humidity, and temperature. For this purpose, various reagents and indicators can be used, including bromothymol blue (BB), curcumin, bromocresol green (BCG), and enzyme-based reagents.

Fish, for example, is sold globally for its high protein content and availability of omega-3 fatty acids. However, with today's busy lifestyle, the consumption of packaged meals has increased dramatically and you need to be sure that packaged fish is still fresh. Sriramulu et al. used temperature-based synthesis in combination with microwave hydrothermal techniques to synthesize CuO nanoflakes, thus solving the fish freshness problem (Sriramulu et al. 2024). Despite their usefulness, bio-based sensors that detect the freshness of food have some limitations due to their cost.

Time–temperature indicators

Time–temperature indicators (TTIs) are instruments used in food packaging to monitor the cumulative exposure of a product to specific temperature ranges over time. These devices help ensure the quality and safety of food during its distribution and storage (Forghani et al. 2021). TTIs exploit chemical, enzymatic or physical reactions sensitive to temperature and time. The rate of these reactions varies with temperature, allowing the TTI to record cumulative exposure to different temperatures over time. These reactions cause a visible change, such as a colour change, which can be easily monitored. The change is gradual and progressive, indicating not only whether the food has been exposed to high temperatures but also for how long (Gao et al. 2020).

They are generally easy to read and interpret, requiring no complicated tools or technical expertise to use effectively. TTIs can be produced relatively cheaply, making them accessible for various applications in the food industry. TTIs are not free from limitations. Indeed, each of them is designed for specific temperature ranges and times, which may limit their universal applicability. Choosing the appropriate TTI type for the particular product and transportation conditions is necessary. TTI indicators can be classified in Table 2 based on the operating principle.

Biosensors for food contamination

Biosensors are now ubiquitous in various sectors, such as biomedical diagnosis for disease monitoring and progression. The use of biosensors in the clinical field presents numerous advantages compared to traditional clinical diagnostics; they have been used as investigation tools for recognizing numerous pathologies, monitoring vital parameters and dietary-pharmacological therapies through the measurement of appropriate biomarkers.

In particular, environmental monitoring and food control are two sectors in which the use of biosensors is continually growing (Koval et al. 2023). In recent years, an imperative need has emerged to improve the sustainability of food packaging; the choice of sensors must also reflect this essential requirement (Bhalla et al. 2016).

A biosensor is a device made up of a biologically active material in contact with a transduction element to detect the activity of chemical species present in a given sample (Kheyraddini Mousavi et al. 2012).

It comprises a bioreceptor and a transducer, as depicted in Fig. 6. A bioreceptor is a molecule (enzymes, cells, microorganisms or antibodies) that specifically recognizes the analyte. The process of generating the signal (it can be in the form of heat, light, pH, change in charge or mass, etc.) following the interaction of the bioreceptor with the analyte is called biorecognition. The transducer converts the

Table 2 Classification and characterization of the main TTI systems in food quality monitoring (Mohammadian et al. 2020)

TTIs type	Function principle	Activation conditions	Storage conditions	Potential drawbacks
Chemical	Polymerization-based TTIs	Room temperature	Low temperature	Cost, toxicity
	Photochromic-based TTIs	Light	Room temperature	Inaccuracy
	Redox reaction-based TTIs	Oxygen	Oxygen free	Inaccuracy
Physical	Diffusion-based TTIs	Mixture	Low temperature	Inaccuracy, cost
	Nanoparticle-based TTIs	Mixture	Low temperature	Cost, toxicity
	Electronic TTIs	Mixture	Low temperature	Inaccuracy, cost
Enzymatic	Acid–base reaction-based TTIs	Mixture	Low temperature	Inaccuracy
	Redox reaction-based TTIs	Mixture	Low temperature	Inaccuracy
Biological	Yeast-based TTIs	Mixture	Room temperature	Inaccuracy
	Lactobacillus-based TTIs	Mixture	Room temperature	Inaccuracy
Others	Thermochromic polymer/dye blends based TTIs	–	–	–
	Photonic lattice changes-based TTIs	–	–	–

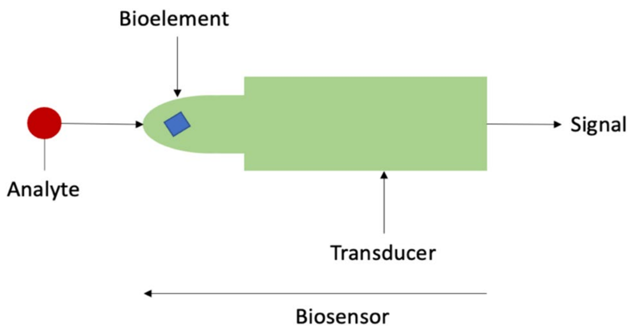

Fig. 6 Basic scheme of a biosensor based on a bioreceptor and a transducer, converting the detected analyte information into a signal

biorecognition event into a measurable signal. This energy conversion process is known as the signalling (Sanponpute and Wattong 2017).

Depending on the mechanism used, different types of transducers can be distinguished (Vasu naik et al. 2017).

Electrochemical transducers. They are further divided into:

1. Potentiometric: such transducers consist of a metal wire wrapped on an insulating support and a mobile contact capable of moving along the conductor. Its operating principle is based on the variation of resistance in an electrical circuit determined by the movement of the object whose position you want to measure;
2. Voltammetric (amperometric): in this case, an increase (or decrease) in potential is applied to the electrochemical cell until an oxidation (reduction) of the substance to be analyzed is observed. This causes a peak in the current of the electrochemical cell, the height of which will be proportional to the concentration of the electroactive material;
3. Conduction: the reaction type measures the conductivity and concentration of a substance containing ions.

Optical transducers. They detect light rays and transform them into electronic signals. In this case, the main techniques used are absorption, luminescence, fluorescence, and SPR (surface plasmon resonance) (Vigneshvar et al. 2016).

Thermal transducers' operating principle involves measuring the heat produced or absorbed by the chemical or biochemical reaction.

Food safety principles are due to the particular advantages of using biosensors. This is thanks to their unique features, a reasonable price considering their high efficiency, and low energy consumption (Pourmadadi et al. 2023).

With the increase in environmental pollution, another concern is the possible contamination of foods caused by contaminants, bacteria, and toxins (Curulli 2021), which can enter the food chain during the production phases. A risk that should not be underestimated is the presence of heavy metal compounds, such as lead or mercury, especially in fish. Not only that, pesticides and veterinary drug residues are also widely used in agriculture, leading to food contamination. Rapid detection of food contaminants has become necessary, and biosensors are a valid alternative for screening foods before the end of their production process. In nature, there are different types of bacteria, including pathogenic and beneficial ones, and they exist in various habitats: plants, animals and humans. Pathogenic bacteria must be detected in the early stages of infection. In this regard, new detection approaches involving bacteriophages as recognition elements are receiving enormous consideration due to the high degree of specificity, accuracy and short analysis time (Hussain et al. 2021). Furthermore, phages are quickly produced and are sensitive to extreme pH, temperature, and organic solvents compared to antibodies. In excellent recent work, recent advances in phage-based bioassays and biosensors, such as the development of a phage-based biosensor for rapid detection of *E. coli* in water (Farooq et al. 2018), have been described. The developed procedures based on molecular biology make phages a distinctive biomaterial for use in diagnostic and research areas, including in the food field, especially in bacterial detection. The sensitivity of phages towards target bacteria makes them ideal candidates for their application in sensor development. Xia et al. developed a fluorescence-based biosensor, using DNA molecules to detect Hg^{2+} ions (Xia et al. 2019). The latter is, in fact, present in large quantities in lakes and fresh water, and inevitably, this metal will easily be found on our plates, endangering our health.

Food safety is a critical public health issue, with bacteria like *Staphylococcus aureus* posing a significant threat by causing foodborne illnesses. In response to this, Farooq et al. have dedicated part of their research to the detection of *S. aureus* in food samples. Their work, which involves the creation of an electrochemical biosensor based on high-density phage particles in surface-modified bacterial cellulose, has the potential to significantly improve food safety by distinguishing live *S. aureus* in a mixture of live and dead cells (Farooq et al. 2020).

Regardless of the technology used, however, all these packaging systems aim to provide the customer and brand with the best experience and complete control over product quality. Although several significant advances have been made in several studies regarding the use of biosensors in this field, and although there is great promise, the challenges in developing smart food packaging are still daunting.

Conclusion and future prospective of smart food packaging

Innovative technology in developing smart biodegradable food packaging is the trend shortly to meet consumers' demand, ever more sensitive to environmental issues and eco-friendly products. Intelligent packaging monitors and provides information about the quality of the packaged food or its surrounding environment to predict or decide the safe shelf life to alert consumers to any food deterioration and contamination. Such packaging systems contain three types of devices: external time–temperature indicators attached outside the package; internal oxygen, carbon dioxide, microbial, and pathogen indicators placed inside the package; and indicators that increase the efficiency of information flow and communication between the product and the consumer.

Smart packaging is strongly attractive and requires a multi-disciplinary approach for the commercialization step, requiring the cooperation of food technologists, microbiologists, chemists, polymer technologists, chemical engineers, and environmental scientists. Most studies on smart food packaging have been conducted at the laboratory scale, and commercial applications are still very limited. Therefore, scale-up production is an essential current challenge, and further research should focus on the industrial implementation of such packaging.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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