frontiers | Frontiers in Sustainable Food Systems

TYPE Review
PUBLISHED 03 August 2023
DOI 10.3389/fsufs.2023.1225371

EDITED BY
R. Pandiselvam,
Central Plantation Crops Research Institute (ICAR), India

REVIEWED BY
Saiful Irwan Zubairi,
National University of Malaysia, Malaysia
Swarup Roy,
Lovely Professional University, India

*CORRESPONDENCE
Misael Sebastián Gradilla-Hernández
✉ msgradilla@tec.mx
Paloma Barajas-Álvarez
✉ pbarajas@up.edu.mx

[†] These authors have contributed equally to this work and share first authorship

RECEIVED 19 May 2023
ACCEPTED 20 July 2023
PUBLISHED 03 August 2023

CITATION
González-López ME, Calva-Estrada SdJ, Gradilla-Hernández MS and Barajas-Álvarez P (2023) Current trends in biopolymers for food packaging: a review. *Front. Sustain. Food Syst.* 7:1225371.
doi: 10.3389/fsufs.2023.1225371

Current trends in biopolymers for food packaging: a review

Martín Esteban González-López[1†], Sergio de Jesús Calva-Estrada[2†], Misael Sebastián Gradilla-Hernández[1*] and Paloma Barajas-Álvarez[3*†]

[1]Tecnologico de Monterrey, Escuela de Ingeniería y Ciencias, Laboratorio de Sostenibilidad y Cambio Climático, Zapopan, Mexico, [2]Departamento de Investigación y Desarrollo, Feliu Chocolate, Guadalajara, Mexico, [3]Escuela de Administración de Instituciones (ESDAI), Universidad Panamericana, Zapopan, Mexico

Non-biodegradable plastics have been extensively used for food packaging due to their outstanding properties that preserve food quality during transportation and shelf-life. The global awareness of plastic pollution has led to the development of environmentally friendly technologies for food packaging such as biodegradable polymers, edible films and coatings, and active or smart packaging. However, the petroleum-based polymers market seems not to be interested in setting back and current waste management strategies continue to be deficient in both technical and economic aspects. This work aimed to provide insights into the state-of-the-art technologies for food packaging based on the advances that have been made to improve the moisture, heat, and barrier properties of novel materials that could close the gap to conventional plastics in terms of performance and costs. This literature review takes a multidisciplinary approach, focusing on the required properties of food packaging and the potential impact on the physicochemical properties of food products. The aim is to identify gaps between current technologies and market demand that impede the alignment of the food packaging industry with global environmental policies. Several sustainable packaging options were identified, such as biopolymers like PLA or PBAT. However, most successful packaging solutions are made up of PVA, chitosan, gelatin, or films based on proteins. In both cases, the addition of essential oils, natural extracts, or nanoparticles to the packaging material has demonstrated its effectiveness in improving performance and ensuring food preservation over an extended period on the shelf. However, a significant research gap has been identified regarding the scaling up of packaging materials based on natural polymers, despite the technology appearing to be sufficiently advanced for practical implementation. Hence, it is necessary not only to optimize parameters to enhance functionality and mechanical properties but to demonstrate their feasibility for industrial production. Furthermore, it is essential to assess their environmental impact. It is important to provide evidence of the feasibility of real-world applications of the new materials developed, demonstrating their effectiveness under critical storage conditions for the preservation of different food groups.

KEYWORDS

biopolymers, microbiology, moisture transport, bioactive compounds, active packaging, smart packaging, sustainable food systems

1. Introduction

Food packaging is essential for protecting food from external conditions, such as temperature, humidity, and light, and maintaining quality, integrity, freshness, and safety during its shelf life by controlling gas and vapor exchange with the atmosphere. The presentation of a food product is crucial for the perception of the consumer regarding freshness and quality, thus controlling their consumption patterns (Rodríguez-Rojas et al., 2019). The most commonly used materials for food packaging are paper, glass, and plastic (Taherimehr et al., 2021). Paper is lightweight, recyclable, and cost-effective, making it ideal for packaging dry foods with low-fat content. Glass is non-toxic, inert, and provides an excellent barrier to oxygen and moisture, making it ideal for packaging products with high acidity or fat content (Ncube et al., 2020). Plastic is versatile, lightweight, and has excellent barrier properties, making it ideal for packaging a wide range of products, including snacks, beverages, and fresh products (Taherimehr et al., 2021).

Plastic is represented in the packaging market by high-density polyethylene (HDPE), low-density polyethylene (LDPE), very low-density polyethylene (VLDPE), polyethylene terephthalate (PET), polyvinyl chloride (PVC), polystyrene (PS), and polypropylene (PP), which account for nearly 90% of total plastic production (Cazón and Vázquez, 2021). Based on the yearly increase in plastic consumption, it is projected that by 2050, the world plastic consumption will reach 500 million tonnes, with single-use items accounting for the majority of this consumption (Ncube et al., 2021). Due to their ease of manufacture, versatility, affordability, lightweight, and low cost, these synthetic polymers have dominated the packaging sector despite being non-biodegradable, thus persisting in the environment for longer than the application they were designed for (Baranwal et al., 2022). Nowadays, the presence of microplastics in the food chain is a huge concern (Ncube et al., 2020). Additionally, the depletion of oil reserves, the increasing awareness towards sustainability, and stricter regulations of municipal solid waste management are driving forces for the replacement of conventional packaging materials and the adoption of more sustainable alternatives.

Several efforts have been made to promote the use of recyclable plastics for food packaging. However, this is especially challenging for primary packages that come in direct contact with food. Contaminants present in recycled plastic must be monitored at sufficiently low levels to ensure food safety, which is costly and time-consuming (Ncube et al., 2021). Besides, some plastics are processed with aluminum foil, making recycling laborious and uneconomical (Din et al., 2020). Additionally, if ink chemicals are not fully eliminated from recycled printed materials, there is a risk that they may persist in packaging made from these recycled materials and eventually migrate into the food (Bradley et al., 2013). In this sense, biodegradable packages are environmentally friendly solutions for green packaging applications because they can be transformed into smaller molecules using biotic and abiotic agents (Ncube et al., 2020).

Biopolymers derived from renewable feedstocks can compete with traditional polymers in terms of functionality and cost. Particularly, packaging for short-term use can benefit from the biodegradable feature of these polymers, considering that plastics are often disposed of alongside food (Baranwal et al., 2022). It is important to note that it is not recommended to dispose of them along with food waste due to potential environmental risks and safety concerns. Proper source separation of solid waste, including biodegradable plastics, is crucial for effective waste management and reduction of pollution (Lara-Topete et al., 2022). However, the "bio" term labeled in many commercial products remains confusing for consumers, as it could refer to the nature of the feedstock from which they are produced, and/or to their end-of-life. Many stakeholders, from governments, producers, and consumers, are suspicious of greenwashing on this topic. Biodegradable polymers are presumably degraded relatively fast by microorganisms under controlled composting environments where moisture and temperature are set accordingly (Taherimehr et al., 2021). This claim is ambiguous due to the troublesome compostability of some polymers such as polylactic acid (PLA), which decomposes in a reasonably long time when littered or disposed of in anaerobic environments such as landfills (Guillard et al., 2018). Hence, the disposal environment is an important factor to consider as the nature of microorganisms and other abiotic factors would determine the extent of degradation (Din et al., 2020).

Even though biopolymers have emerged as promising materials that can serve the same purpose as conventional plastics, their low market uptake persists either because of some performance drawbacks or a lack of applicable measures targeting single-use food packagings plastics, such as regulations or incentives that encourage their adoption, and education and awareness campaigns targeting both consumers and manufacturers (Walker et al., 2021). In 2019, global bioplastic production accounted for which accounts for a mere 0.6% of total plastic production as per the report by the European Bioplastics Association (Fredi and Dorigato, 2021). Besides, several physicochemical properties must be preserved by food packages to increase the product's shelf life, avoiding spoilage, oxidation, and preserve quality factors, such as color, texture, nutritional value, and quality, which are crucial factors for the acceptance and safety of the product (Kumar et al., 2022). Among the many important properties that must be considered for packaging material, e.g., transparency, thermal resistance, and mechanical performance, among others, barrier properties are key for preserving a suitable atmosphere inside the package headspace, as it is a key factor in ensuring that the packaged material remains fresh and safe for consumption. However, most biodegradable packaging materials lack suitable barrier properties to preserve food quality and freshness. For instance, PLA is the most representative example of biodegradable packaging, however, its barrier properties are not sufficient to meet the requirements for the preservation of food products. PLA has relatively poor water vapor and oxygen barrier properties, which makes it unsuitable for packaging products that require long shelf life (Iglesias Montes et al., 2019). Hence, to replace conventional plastics with biopolymers in the food packaging industry, it is essential to overcome the gas and vapor permeability issues of most biodegradable packages (Taherimehr et al., 2021).

Over the last decades, several reviews have been published regarding the state-of-the-art developments in the field of food preservation and packaging. As demonstrated by Rodríguez-Rojas et al. (2019) research focused on food packaging materials has significantly grown in the last decades. These authors identified that the most popular keywords regarding this topic were related to antimicrobial and active packaging, while they also identified future trends regarding modified atmosphere packaging (MAP). Cheng et al. (2022) described different smart packaging materials, including sensors to detect alterations in food properties, and discussed their application in the food industry. However, any information about legislation packaging or mechanical properties of such materials was presented. Bhargava et al. (2020) summarized different studies that use food pigments to fabricate intelligent and active packaging films in combination with biopolymers, and presented the advantages and disadvantages of such materials. However, this review only presents natural materials and the sensibility of these pigments to changes in the packaging microenvironment, without providing solid considerations regarding the real-world application of those materials. Cazón et al. (2017) described the use of polysaccharides for food packaging and their properties. However, they concluded that the properties of these packaging materials are poor and highlighted the need to combine them with other polymers to enhance their properties. Recently, Prasad et al. (2024) reported the use of nanoemulsions for active packaging for food products; they concluded that further research on the application of this technology on the surface of fruits and vegetables is necessary prior to scaling up and application. Regarding more mature technologies, Asgher et al. (2020) summarized the advances made in using biopolymer-based coatings and films for food packaging based on microbial polymers, wood-based polymers, and protein-based polymers. They concluded that to reach the desired functionality, blends or composites of different polymers have become an emergent research trend, aiming to improve the mechanical and barrier properties. Xie et al. (2022) reported the main characteristics of different biopolymers used for active and intelligent packaging in muscle foods. They concluded that further research needs to be conducted to achieve the application of these technologies. Yadav et al. (2021) reviewed the use of edible materials from fruit waste and emphasized the significance of physicochemical properties in films. They determined that scaling up the film formation process with economic viability is necessary, and using underutilized waste could help reduce the production cost. This brief literature review reflects that many efforts have been made in terms of developing new packaging materials, although the cases of success that have scaled up the technology and applied it at industry level are considerably less. Also, it is noteworthy that the petroleum-based polymer market seems to not be interested in setting back despite the extensive research conducted in the field of biopolymers for food packaging applications.

Although numerous review papers have successfully addressed the technological advancements related to biopolymer-based packaging and active and intelligent packaging, there have been fewer studies demonstrating the technological feasibility of scaling up and implementing such materials in actual food systems. To the best of our knowledge, no studies have compiled research on biopolymer-based food packaging technologies that are at a technology readiness level closer to real-world applications. Therefore, the objective of this work is to provide insights into state-of-the-art technologies for food packaging by highlighting efforts done to enhance the packaging features of sustainable materials, with the aim of bridging the performance and cost gap between these materials and conventional plastics, ultimately enabling their practical use. Recent reports on novel biopolymer-based packaging materials were critically assessed to include only those with strong potential for application based on their physical and mechanical properties, as well as their demonstrated positive impact on protecting food products throughout their shelf life. The novelty of this comprehensive review is the multidisciplinary approach, focusing not only on the necessary properties of the packaging but also on its influence on the physicochemical properties of food products. The ultimate goal is to identify the challenges that impede the alignment of the food packaging industry with the food industry market and global environmental policies. Consequently, this review also discusses relevant legislation and actions pertaining to sustainability.

2. Generalities of food preservation

Food packaging plays a critical role in ensuring the safety of food supply worldwide by preserving the properties and integrity of the product from the time it is processed until it is consumed. Additionally, packaging technology must consider a balance between design and functionality while also taking into account energy and material costs, social and environmental impact, and compliance with regulations and requirements for its proper disposal (Seyfzadeh et al., 2013). Packaging is categorized into three main categories according to their function and purpose in the supply chain: primary packaging refers to the materials that come into direct contact with the product and are handled by the end consumer. Secondary packaging groups individual units for transportation and display of the product at retail. Finally, tertiary packaging is used for the storage and handling of secondary packaged products (Wypij et al., 2023). Primary and secondary packaging are essential for preserving the quality and extending the shelf life of food products (Wypij et al., 2023). However, since primary packaging comes into direct contact with food products, it must meet strict regulatory requirements to ensure that it does not pose a risk to public health. Hence, recycling is limited for primary packaging as it has raised concern to the U.S. Food and Drug Administration (FDA) due to the direct contact with food.

In this sense, the migration of chemical compounds such as printing ink present in the packing film into the foods is an essential parameter to consider for both pristine and recycled packaging materials. While the inks and lacquers are typically applied externally on the packaging material, it is still possible for low molecular weight substances to diffuse through porous packages and migrate into the food (Bradley et al., 2013). While antioxidants and organophosphite antioxidants are vastly used in printing inks, photoinitiators (PI) are specifically concerning additives used to produce light-curable products such as UV-curable inks (Liu and Mabury, 2021). PI raised food safety alarms when 2-isopropylthioxanthone was detected in contaminated milk in Europe in 2005. PI may persist in food packages and permeate from non-food contact surfaces into food (Zhang et al., 2016).

Some factors that affect the migration of these contaminants are the packaging material, the physicochemical properties of the contaminated agent, the type of food, the time and temperature of storage, and the food dimensions. Therefore, it is essential to monitor and develop a legislative framework for the materials and chemicals used in primary food packaging and to eliminate the potential sources of contamination. A clear example is the European Union guidelines on Regulation (EU) No 10/2011, which pertain to plastic materials and articles intended for food contact, that do not provide specific control measures for PIs. In this sense, the European Printing Ink Association released a suitable list of PIs for low-migration UV printing inks in 2013. Additionally, the Rapid Alert System for Food and Feed has issued notifications regarding the migration of PIs from food packaging (Zhang et al., 2016).

The migration of ink into food could affect the sensory properties of food, compromise food safety, and modify the quality and nutritional value of the food by the contaminated compound (Alamri et al., 2021). In terms of food safety, Bradley et al. (2013) reported that several inks compounds were present in different foods such as milk and cinnamon powders, muesli, cheese, and chocolate, among others. Also, they reported the migration of benzophenone (toxic PI) in 37 food products. Moreover, Scarsella et al. (2019) reported the presence of 2,4,6-trimethylbenzaldehyde, 1-phenyl-2-butanone, 4-methylthiobenzaldehyde, and benzaldehyde in several food packaging samples products of photolytic decomposition. Several products of this decomposition have novel structures leaving regulatory authorities without the data required for evaluating migration levels and toxicity. For that reason the current lack of toxicological information related to the safety of these products (Scarsella et al., 2019). However, the Overall Migration Limit provided by the EU Commission is 60 mg/kg of food, or 10 mg/dm^2 of all substances in the food (De Tandt et al., 2021).

Some strategies to overcome the migration and contamination of food with ink were the use of lacquers as an extra barrier, water-based inks, UV-curing inks, or the use of ink produced with natural or nature-compatible materials (Aznar et al., 2015; Ozcan and Arman Kandirmaz, 2020; Hakim et al., 2023). For instance, Ozcan and Arman Kandirmaz (2020) synthesized red-magenta dye from red beet thus obtaining inks that could be used in smart packaging materials. Similarly, Hakim et al. (2023) use *Senegalia catechu* as a substitute for synthetic pigments. Hence, the replacement of solvent-based inks by safer water-based inks driven by the awareness of avoiding food contamination goes in hand with the advent of sustainable food packaging materials.

When developing food packaging materials, the supplier must consider a complete set of product characteristics, including its physical, chemical, biochemical, and enzymatic nature, organoleptic characteristics that define its quality, and risk factors such as physical, chemical, and microbiological factors that can compromise the stability of its properties during storage. Hence, the development of new packaging materials for food should initially prioritize understanding the four critical characteristics that indicate the quality of food: its color, aroma and flavor, texture, and microbiological safety (Figure 1).

2.1. Color

Color represents an important indicator of food quality due to its easy perception by the consumers' eyes. In the case of fruits and vegetables, color reflects their freshness, integrity, and maturation stage, as it is associated with natural pigments such as chlorophylls, carotenoids, anthocyanins, flavonoids, and betalains. These pigments undergo chemical changes when exposed to environmental factors such as temperature, oxygen, pressure, light, and physical, chemical, or microbial damage (Barrett et al., 2010). In meat, color indicates oxygenation and freshness associated with myoglobin concentration, and the alteration of its color is associated with oxidation, loss of freshness, or microbial contamination (Oliveira Xavier et al., 2021). However, in some fruits and vegetables, color changes indicate the oxidation of certain compounds, such as chlorophyll pigments that change from green to brown or anthocyanins that change color depending on pH levels. In this sense, the transparency of the packaging is key for the consumer to evaluate the real quality of the product based on its appearance, avoiding opacity and color changes that lead to consumer confusion or loss of sensory acceptability (Ncube et al., 2020). For this reason, plastic films are the most commonly used primary packaging materials due to their unique properties that provide excellent protection to food products while allowing consumers to evaluate their quality. The transparency of plastic films enables consumers to evaluate the product's real quality based on its color. Additionally, plastic films can be manufactured in a variety of thicknesses, allowing for the customization of the packaging to meet specific product needs (Alias et al., 2022). The use of plastic films also allows for easy printing of branding,

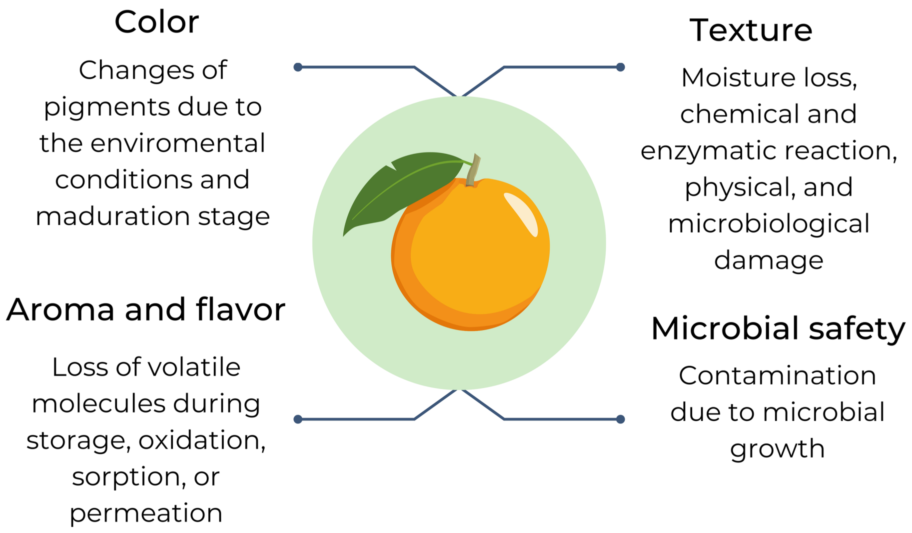

FIGURE 1
Quality characteristics to be preserved in food packaging.

nutritional information, and other necessary product information, making them an attractive option for food manufacturers.

2.2. Aroma and flavor

Consumers typically enjoy experiencing pleasant aromas when they first open a package (Ozdemir and Floros, 2004). Compounds responsible for aromas and flavors are often highly volatile molecules of low molecular weight that can be easily lost during product storage as a result of chemical reactions within the food matrix, such as oxidation of its components, or by sorption or permeation through the packaging. To preserve the typical organoleptic characteristics that define the product's quality over time, a packaging material with efficient barrier properties to these types of compounds is required. This is essential to maintain the product's sensory acceptability and prevent flavor and aroma degradation (Fabra et al., 2008; Ammala, 2011). Among the packaging materials commonly used, films, coated papers, and multilayer structures have outstanding barrier properties. These materials, including PET and polyethylene (PE), are known for their ability to prevent the transfer of gasses and other volatile compounds, thus helping to maintain aromas and flavors for an extended period (Salgado et al., 2021).

2.3. Texture

The texture is among the most important attributes that significantly impact the acceptability of food. It is a property that depends on the proportion of solids (carbohydrates, proteins, lipids, minerals, fibers), water, and gas content (carbon dioxide, air, and nitrogen) so that the initial composition of food defines unique textural properties that the consumer can relate to acceptable conditions for consumption. Texture changes in foods are caused by moisture loss, chemical, and enzymatic reactions, or physical and microbiological damage during storage (Chen and Opara, 2013). Some of these factors are affected by the handling and operation of the product, while others are associated with storage conditions (temperature, relative humidity, pressure), as well as the type and material of its packaging.

2.4. Microbiological safety

Ensuring food safety is of utmost importance as contamination and microbiological growth in food can lead to physical and chemical changes that compromise its quality, resulting in economic losses. The presence of high microbiological loads or the production of toxic metabolites can pose significant risks to the health of the consumer. Food products such as fruits, dairy products, certain bakery items, and meats, among others, generally contain enough moisture to create a water activity that can facilitate the growth of potentially harmful microorganisms under ideal conditions, including temperature, oxygen, and pH, from the point of harvest to production, packaging, transportation, and storage. This growth of microorganisms can result in physical and chemical changes, affecting the quality of the product and leading to economic losses. Additionally, it can pose a significant risk to the health of consumers due to the microbiological load or production of toxins (Mousavi Khaneghah et al., 2018). Some of the most commonly used materials for ensuring microbiological safety in food packaging include PET, HDPE, LDPE, and PP. These materials have a high barrier capacity against moisture and gasses, which helps prevent the growth of microorganisms that can contaminate and spoil the food.

However, contaminants found in printed or labeled packaging, such as ink components or chemicals, can foster the degradation and decrease the quality of food by initiating enzymatic or chemical reactions. Certain ink components have the potential to interact with the constituents of the food, which can accelerate oxidative processes. As a result, fats, oils, and other vulnerable components in the food can break down more rapidly, leading to the development of off-flavors and the onset of rancidity. Besides, the preservation of the quality characteristics of food mentioned earlier requires a high level of regulation and control over the transfer of water vapor and gasses between the environment and the product. This is particularly important to ensure microbiological safety, as well as to prevent the loss of aroma and flavor and maintain the desired texture and color. However, it is important to note that different food products have varying requirements for gas permeability and water vapor transmission rates, depending on their composition and the specific environmental conditions in which they will be stored or transported. For instance, some products may require a high level of oxygen transmission, while others may need to be stored in an environment with low oxygen levels to prevent spoilage. Therefore, it is crucial to select packaging materials with appropriate gas permeability properties to suit the specific needs of each product and ensure its quality and safety throughout its shelf life.

3. Gas permeability in food preservation

The quality and shelf life of packaged products are both directly affected by the permeability of packaging materials to volatile substances (Phothisarattana et al., 2021). Different food groups have varying gas permeability requirements for their packaging, such as barrier properties against water vapor, oxygen, and other volatile compounds (Figure 2). These requirements present the challenge of developing packaging materials that cater to the specific permeability needs of each product. The following sections describe the adverse effects that gasses and volatile compounds can have on food products, as well as the efficient barrier properties of packaging materials that prevent such effects and extend the shelf life of food products.

3.1. Water vapor

Moisture is related to freshness and has an important effect on the initial net weight of the food. Moisture conservation is crucial to prevent changes in texture and weight loss of a product, thus extending its shelf life, and reducing economic losses, without ignoring that high moisture levels provide a favorable environment for microbial growth, risking food safety (Yousefi et al., 2019). For instance, moisture loss in baked foods results in an increase in their hardness by the staling phenomenon caused by the retrogradation of starch and the migration of water from the starch to proteins (Balaguer et al., 2013;

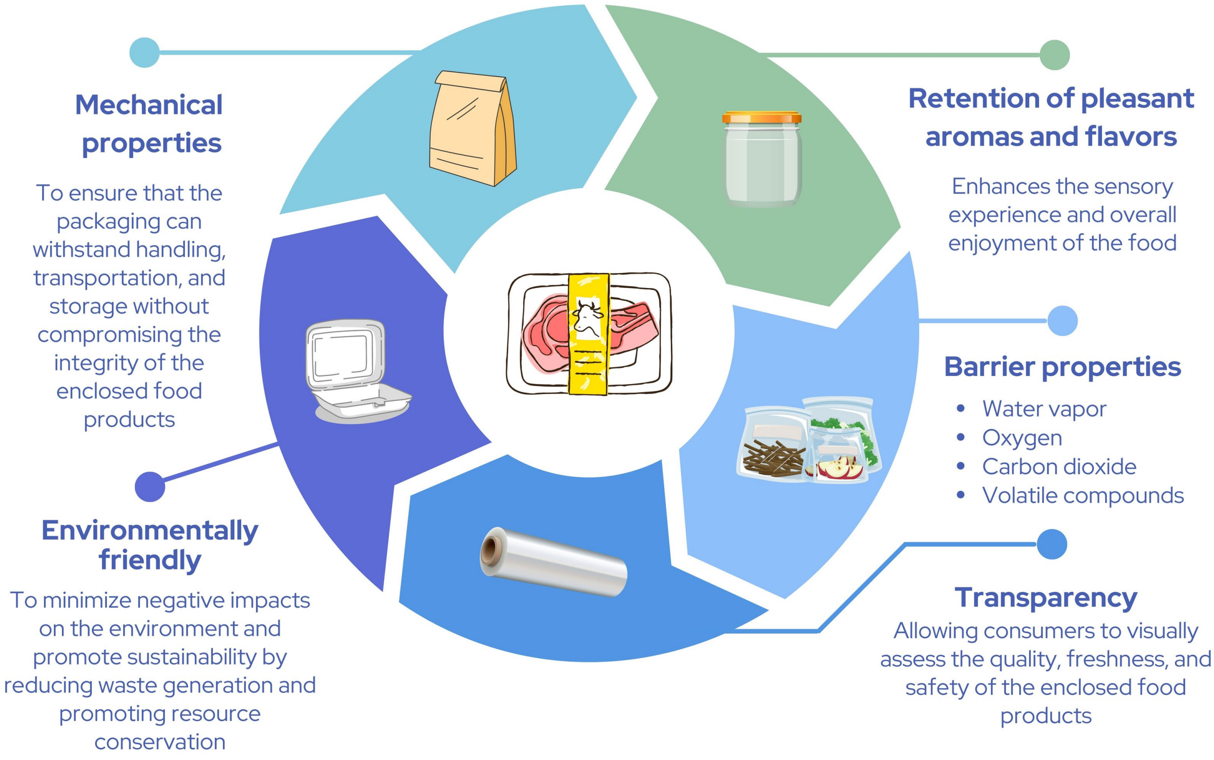

FIGURE 2
Main characteristics of food packaging materials.

Calva-Estrada et al., 2021; Bumbudsanpharoke et al., 2022). This phenomenon affects the crisp and crunchy texture of dry foods and some baked products whose texture is affected when the products exceed their water activity by plasticization of the food matrix, ultimately causing consumer rejection (Rossi Marquez et al., 2014). In fresh or frozen meat, the loss of moisture causes changes in the texture due to dehydration, which favors the oxidation of its components and compromises its color and flavor (Battisti et al., 2017). Besides, fruits, vegetables, and fresh-cut products are highly susceptible to water evaporation during storage due to respiration and transpiration phenomena, which leads to product weight loss that in turn translates into economic losses, decreased hardness, and deterioration of its fresh texture and appearance (Mohebbi et al., 2012; Azhar Shapawi et al., 2021; Efthymiou et al., 2022).

In summary, avoiding or decreasing moisture transfer between food and the atmosphere in the surrounding area is critical to maintaining food quality and safety. Accordingly, a suitable water vapor permeability (WVP) determines the packaging potential and effectiveness of a material for a particular type of food in terms of preventing moisture loss. Polymer films used for food packaging purposes can be classified according to a range of WVP values as poor (0.42–4.2 $g\,mm\,m^{-2}\,h^{-1}\,kPa^{-1}$), moderate (0.0042–0.42 $g\,mm\,m^{-2}\,h^{-1}\,kPa^{-1}$), or good (0.00042–0.0042 $g\,mm\,m^{-2}\,h^{-1}\,kPa^{-1}$). Traditional polymer packages like LDPE and HDPE have good WVP values of 0.0040 $g\,mm\,m^{-2}\,h^{-1}\,kPa^{-1}$, and 0.0012 $g\,mm\,m^{-2}\,h^{-1}\,kPa^{-1}$, respectively (Battisti et al., 2017), which faces a challenge to new packaging materials that are designed for this purpose.

3.2. Oxygen

The barrier capacity against molecular oxygen (O_2) is a determining factor that guarantees the maximum shelf life of food products (Bugnicourt et al., 2013). Oxygen is a gas that participates in oxidation reactions of different food components such as fats, proteins, pigments, vitamins, aromas, and flavors. Moreover, it acts as a substrate of oxidizing enzymes and contributes to developing aerobic microorganisms, including fungi, causing the loss of nutritional content and sensory quality of the product, compromising its safety and shelf life (Daniloski et al., 2019; Horman et al., 2022). Oxidation of lipids and myoglobin constitute the main factors that cause the deterioration of meats, such as beef and tuna, during refrigerated storage. This oxidation causes rancidity, which is associated with unpleasant odors and flavors, and changes in the meat color from red to brown due to the formation of metmyoglobin derived from the oxidation of myoglobin, which reduces quality and product acceptance (Kaewprachu et al., 2017; Oliveira Xavier et al., 2021). Also, the oxidation of meat proteins impacts their solubility, which leads to their aggregation and formation of cross-linked complexes, increasing the hardness of the product (Kaewprachu et al., 2017). In fruits, vegetables, and mushrooms, O_2 presence activates enzymes, such as polyphenol oxidase, that oxidize phenolic compounds producing dark pigments that cause unfavorable changes in sensory characteristics of foods, which translate into significant economic losses for the industry due to low consumer acceptance of the product (Singh et al., 2018; Zhu et al., 2019; Taherimehr et al., 2021). Currently, the most commonly used polymers in food packaging systems for O_2-sensitive products are ethylene vinyl alcohol (EVOH), polyvinylidene chloride (PVDC), PET, and polyamide-6 (nylon), used either as coextruded or laminated films and coatings (Popović et al., 2012; Cinelli et al., 2014). The value of 25.3 $cm^3\ m^{-2}\ day^{-1}$ at 1 bar corresponds to the O_2 permeability from a laminated PVDC/biaxially oriented polypropylene (BOPP) 20 μm/PE film of 20 μm thickness represents one of the lowest permeability values of synthetic food packaging materials compared to neat PE and BOPP, constituting the reference value to overcome by new biodegradable materials.

3.3. Carbon dioxide

Carbon dioxide (CO_2) is another gas of great importance to regulate for the proper preservation of food. CO_2 is usually added artificially into the packaging of several foods and kept at adequate levels to obtain favorable effects, such as antimicrobial activity, aiming to preserve quality and to prolong shelf life (Lee et al., 2022). In fruits and derived products, the production of simple molecules of CO_2 and water results from the oxidative breakdown of the organic substrate of the fresh products through its continuous respiration throughout its shelf life. In general, low permeability to O_2 and CO_2 is beneficial for food packaging (Chang et al., 2021).

It has been observed that a packaging material that presents a permeability such that it preserves a low concentration of O_2 and a high concentration of CO_2 inside the package, leads to a decrease in the rate of respiration, ethylene production, and the enzymatic activity of the fruit, thus allowing to store products for a longer time. For this purpose, polymer films such as nylon have shown optimal performance, especially those with permeability coefficient to CO_2 in ranges between $8 \times 10^{-10}\ cm^2\ s^{-1}\ bar^{-1}$ (Craster and Jones, 2019; Azhar Shapawi et al., 2021). In addition, recent studies suggest that the design and selection of new packaging material alternatives for food preservation should focus on a low CO_2 to O_2 permeability ratio since the variability of CO_2 permeability can have a significant impact on the reduction of microbiological growth, contrary to what was observed with O_2 permeability (Hutchings et al., 2021; Lee et al., 2022). Fresh and fermented foods as well as beverages continuously generate CO_2 during storage. This requires the use of packaging solutions with precise permeability to allow the controlled release of this gas, which helps to maintain the quality of product. Moreover, it ensures the physical integrity of the packaging by preventing the accumulation of CO_2 (Din et al., 2020).

3.4. Volatile compounds and other gasses

Another important aspect to consider in the design of materials for food packaging is the retention of compounds related to the pleasant and characteristic aromas of the fresh product, as well as the blocking of foreign odors from the outside that might end up decreasing quality. Polymers that are currently applied with efficiency for this purpose include PVDC, nylon, and PET (Ammala, 2011). Some synthetic packaging materials that have shown efficiency in retaining key aroma compounds (such as neral, geranial, anethole, eucalyptol, and eugenol) from herbal products and spices have been laminated films made of PVDC-coated PET/casted polypropylene, and PET/PET/aluminum foil/linear low-density polyethylene (LLDPE). Generally, these films have low permeability to O_2 (between 0.2 and 4 $cm^3\ m^{-2}\ day^{-1}\ atm$) and water (between 0.25 and 0.5 $g\ m^{-2}\ day^{-1}$), which further favors the chemical stability of aroma compounds (Chaliha et al., 2013). The challenge lies in the fact that each food has a key aroma compound of different nature and its permeability will depend on its way of interacting (through diluting or adsorbing) with the structure of each polymeric material that the development of new packaging must consider.

Nitrogen (N_2) is an inert gas associated with the inhibition of the growth of aerobic microorganisms in food when it is introduced artificially for air (mostly oxygen) removal into the headspace of the packaging (Miranda et al., 2019). Therefore, a packaging material that allows N_2 to be retained as inert gas within the container reduces the food degeneration rate (Salehi et al., 2018; Romero et al., 2019), resulting in an interesting candidate for food packaging under a MAP (Guidotti et al., 2019). Current use of packaging material in foods such as the LDPE film presents a permeability coefficient to N_2 of $1.27 \times 10^{-3}\ mL\ m\ m^{-2}\ h^{-1}\ (0.1\ MPa)^{-1}$ (Chen et al., 2019).

In general, the synthetic plastic materials currently used by the industry fulfill the function of physical protection, transport, and handling of food due to their great resistance and flexibility, in some cases. However, considering that its primary function is the adequate conservation of the product, it is still inefficient due to problems associated with gas permeability issues. In the subsequent section, an examination of alternative biodegradable polymers is undertaken, elucidating their potential as environmentally sustainable and highly efficient packaging solutions. In the following section, an in-depth analysis of alternative biodegradable polymers is conducted, focusing on their potential as environmentally sustainable and highly efficient packaging solutions. By exploring these polymers and their capabilities, this research seeks to provide insights into viable options for sustainable packaging practices.

4. Alternative biodegradable polymers

Bioplastics encompass materials that are either bio-based, biodegradable, or compostable, making them highly regarded as one of the most appealing alternatives to fossil-based polymers (Visco et al., 2022). Food quality is tightly linked to the employed packaging since during storage and transportation, food packaging must be resistant to external conditions while limiting gas transport (Modi et al., 2021). The food packaging sector is mainly covered by common plastic materials such as PET, PVC, PE, PP, and PS (over 40% of the worldwide plastic market) due to their exceptional barrier properties, mechanical performance, and tolerance to thermal and oxidative degradation. While biopolymers have a biodegradable feature that addresses the issue of plastic pollution, their lack of strength, flexibility, and most importantly, barrier properties to O_2 and water vapor have hindered their widespread adoption in the market, not to mention their expensive cost poses another important challenge (Porta et al., 2020). As mentioned above, the transmission rate of gasses and water vapor from the outside to the package affects the packaging potential of alternative packaging material (Din et al., 2020). A clear example is paper and board materials used for packaging, which exhibit very high gas and moisture diffusivity, restricting their applications for some foods. Therefore, there is a growing interest in exploring new alternatives to conventional polymers, such as those obtained through synthesis or renewable natural sources, including agro-industrial waste. These alternative biodegradable polymers have the potential to improve their properties, making them suitable for scaling up their industrial applications in the food packaging sector. Figure 3 depicts some types of natural and biodegradable polymers that can be used for developing biocomposites in food packaging applications. These biocomposites are blended with natural oils and extracts to provide antimicrobial or antioxidant properties, resulting in what is known as active and/or intelligent packaging. The following sections describe in detail the characteristics of synthetic and natural polymers that have been used as matrices for active packaging in the last few years.

4.1. Synthetic polymers

Polylactic acid (PLA), Polyhydroxyalkanoates (PHAs), Polyvinyl alcohol (PVA), Polybutylene succinate (PBS), copolymers or blends of these polymers, and several natural polymers have emerged as promising alternatives to conventional polymers. PLA is a synthetic polymer that is known for its flexibility, high transparency, ease of processing, and recyclability. Its chemistry makes it biodegradable through hydrolysis of ester linkages, and sensitive to temperature. These characteristics make PLA suitable for environmentally friendly food packaging applications. It has been widely used for shopping bags, cups, trays, and wrapping films, being processed by common thermoplastic methods, e.g., extrusion, thermoforming, injection molding, and film blowing, among others. It is presumably biodegraded within 3–4 weeks under controlled composting conditions. However, recent studies have shown that PLA degradation could take as much as 3–5 years depending on the degradation environment (Ncube et al., 2020). Considering that many of its applications are single-use primary packaging, PLA's end-of-life must be assessed before its implementation (Ncube et al., 2020). In addition, the environmental implications of PLA recycling methods must be considered based on life cycle assessment (LCA) (Pérez-Fonseca et al., 2023). Besides, due to its high gas permeability and poor barrier properties, PLA is not applicable for some applications such as beverage bottles, whose market is dominated by PET bottles (Modi et al., 2021).

PVA is a biodegradable polymer that is commonly used due to its non-toxic and biocompatible nature. It is a water-soluble polymer with excellent film-forming properties due to the hydroxyl groups that enable water solubility and the formation of transparent films, making it suitable for food packaging applications. However, its high cost compared to other synthetic polymers makes it less desirable for use in packaging applications, and it often needs to be blended with other polymers to improve its performance. Additionally, PVA has poor mechanical and barrier properties, especially in humid environments, which further limits its potential use in packaging (Sánchez-Gutiérrez et al., 2021; Li et al., 2022). PHAs such as polyhydroxybutyrate (PHB) possess similar mechanical properties as PE, but their lamellar structure provides higher aroma barrier properties which are useful for short-term food packaging. Besides, PHAs exhibit diverse properties depending on the specific monomers incorporated during biosynthesis, offering a wide range of potential applications in food packaging. Life cycle assessment has demonstrated that these polymers emit less CO_2 in their production process than the captured carbon, generating an important environmental impact considering a cradle-to-grave perspective (Rekhi et al., 2022). These polymers can be molded into soft films or strong plastics by conventional processing methods to produce cups, jars, trays, or single-use packaging utensils (Rekhi et al., 2022). PBS is a biodegradable polyester useful in the packaging industry because it is resistant to heat and light, along with easy processability. However, the low impact strength and tear resistance limit its application. Highly amorphous PVA, commonly referred to as polymer-G, represents an eco-friendly polymer with

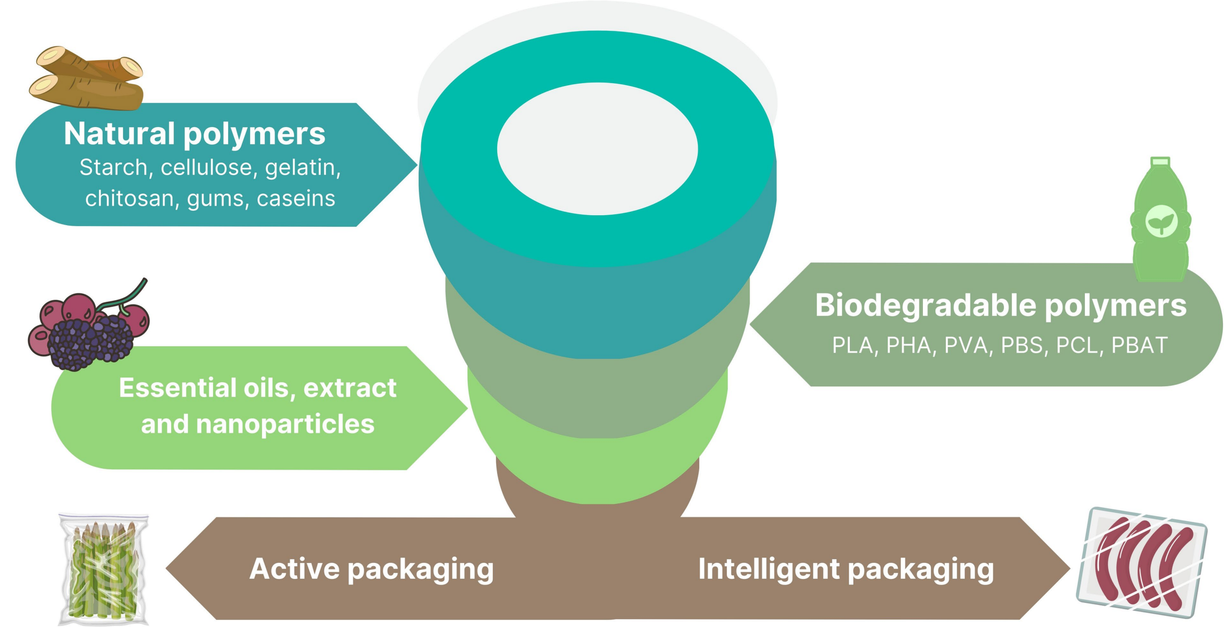

FIGURE 3
Natural and biodegradable polymers for developing active food packaging.

substantial implications for the food packaging industry. This is due to its biodegradable nature and superior properties when compared to PVA, which is the most frequently used water-soluble polymer in the field (Mariño-Cortegoso et al., 2022). Poly (butylene adipate-co-terephthalate) (PBAT) is a biodegradable copolyester that combines the properties of polybutylene adipate (PBA) and polyethylene terephthalate (PET), thus it is a copolymer with high deformation capacity, presents mechanical properties comparable to PE, and is stable under regular processing conditions, being considered a promising biopolymer for use in food packaging.

Polyesters like poly-ε-caprolactone (PCL) are biodegradable, rigid, and brittle polymers that find current use in agriculture and packaging. However, they exhibit high permeability to gasses such as O_2 and CO_2, with 3.7- and 2.8-fold higher permeability, respectively, compared to PBAT. Nonetheless, PCL has better biodegradation capacity, with complete disintegration occurring after 41 days in burial soil (Sousa et al., 2022). Thermoplastic starch (TPS) is often blended with plasticizers to increase its processability. However, TPS films are sensitive to moisture and exhibit low mechanical properties, thus it is necessary to blend TPS with other materials to produce a superior material for several applications (Nazrin et al., 2020). In fact, TPS, PLA, or PBS are not recommended for food packaging when used alone due to their low oxygen barrier properties. Hence, biomaterials are formulated into biocomposites to compete with conventional plastics for food packaging applications.

Generally, composites and nanocomposites based on synthetic polymers, reinforced with plasticizers, fibers, layered silicates, metal oxide nanoparticles, or phenolics exhibit improved barrier, mechanical, and functional properties as packaging materials, depending on the type, dispersion, and concentration (Taherimehr et al., 2021). Acetyl tributyl citrate at a concentration of 15 wt.% improves the mechanical properties of PLA by acting as a plasticizer, offering a tensile strength (TS) between 25 and 35 MPa, and an elongation at break (EAB) of 140%–180%, both values are comparable to LDPE (TS of 10–20 MPa, and EAB of 80%–500%) (Aragón-Gutierrez et al., 2020). Similar effect was observed with cholecalciferol at a concentration of 5 wt.% allowing to obtain a material with excellent UV blocking property and improved mechanical properties by enhancing the EAB (11%) by two-fold compared to neat PLA (EAB of 3%), and its TS value (PLA/cholecalciferol film: 38 MPa; neat PLA film: 26 MPA) (Lawal et al., 2023). PVA/Corn starch composite blend films reinforced with methyl methacrylate-grafted *Grewia optiva* fiber at a concentration of 15 wt.% conferred greater adhesion to the matrix, increasing its thermal stability, and mechanical properties. In addition, the composite still showed interesting biodegradability (with a loss of 29% of its weight after exposure to the soil for 120 days under prevailing environmental conditions) (Singha et al., 2015). Fillers such as glass flakes, at 5–25 vol%, added into PVA films favored a reduction of up to 80% in its value of water vapor transmission rate (WVTR) ($1.2–6.2\,g\,m^{-2}\,day^{-1}$) compared to the neat PVA (WVTR of $22.5\,g\,m^{-2}\,day^{-1}$), accelerates its biodegradability capacity in burial soil, and has shown greater food preservation effectiveness compared to commercial LDPE bags (Channa et al., 2022). The mechanical, thermal, and barrier properties of PHB were enhanced with the addition of graphene nano-platelets at an optimal concentration of 0.7 wt.%. Compared to neat PHB, this material showed a 2-fold increase in TS, which is required for packaging heavy food products, a 10°C increase in thermal stability, essential for packaging food at elevated temperatures, and a 3- and 2-fold reduction in O_2 and water permeability, respectively, without compromising the biodegradable feature of PHB, which was wholly degraded in 30 days under a soil burial method (Manikandan et al., 2020). Nanocellulose has reduced the WVP of PVA by 38%–59% and drastically decreased its Oxygen Transmission Rate (OTR) to $0.06–0.08\,cm^3\,m^{-2}\,day^{-1}$, a value comparable to aluminum layer and plastic films such as PET/aluminum oxide and PET/silicon oxide (Sánchez-Gutiérrez et al., 2021). Furthermore, when PVA/nanocellulose composites are crosslinked with ethanedioic acid, the thermal stability of the composite was improved (maximum thermal decomposition temperature of 356–364°C), as well as its WVTR ($\approx 700\,g\,m^{-2}$) was significantly decreased compared to neat PVA (maximum thermal decomposition temperature of 275°C, and WVTR of $\approx 850\,g\,m^{-2}$) (Chin et al., 2022). Finally, PBAT composite film with epoxidized soya bean oil and encapsulated lignin/tannic acid as filler increased by more than 100% the TS and reduced the WVTR and OTR of neat PBAT film offering a potential solution to some of the limitations of use for this polymer in food packaging (Olonisakin et al., 2023). It is evident that composites derived from synthetic polymers have successfully addressed some of their limitations, particularly their low O_2 and water vapor barrier capacity, improved their thermal stability, and accelerated their biodegradability. Nevertheless, the search for more sustainable and cost-effective polymer alternatives that align with the principles of a circular economy has prompted a growing interest in polymers derived from natural and waste sources. Current research is focused on exploring such alternatives as discussed in the following section.

4.2. Natural and agroindustrial waste polymers

The search for alternatives from renewable sources and the utilization of agro-industrial waste for reducing landfills has led to an interest in exploring the potential of using structural and functional hydrocolloids, which are abundantly available in nature, such as proteins (gelatin, caseins, zein, gluten, isolates from seeds) and polysaccharides (starch, chitosan, gums, agar, carrageenan, cellulose derivatives) obtained from animal and vegetable sources, by-products, and agro-industrial residues (bones, skin, feathers, shells, and scales of animals, whey, fruit peels, seed hulls, waste potato starch, between others) (Yadav et al., 2021; Wypij et al., 2023). This group of polymers offers the potential for the development of biodegradable materials. Derived from Generally Recognized As Safe (GRAS) products, they can have direct contact with food and can even be edible along with it (Onyeaka and Nwabor, 2022; Kazemi et al., 2023). This provides an opportunity to create primary packaging in the form of preformed materials that can either cover the product (such as films) or form coatings directly on the surface of the food (Kumar et al., 2022).

Generally, packaging materials developed with polysaccharides and proteins have shown an effective barrier function in the permeation of different gasses, mainly O_2, and aromas. However, in most cases, these materials lose their properties in high-humidity environments (due to the hydrophilic structural groups that constitute them) and they tend to have mechanical properties that can barely compete with the strength offered by plastic materials in current industrial use. For this reason, recent studies have focused on exploring the integration of several technologies, such as the formulation of biocomposites (by blend or laminated) that take advantage of different properties of materials (like polymer blends, lipids, particles, cross-linkers, and plasticizers) to compensate the limitations that each one usually presents in isolation. Also, nanotechnology is focused on obtaining structural materials with greater homogeneity and structural interaction (Xiao et al., 2021; Kumar et al., 2022; Zhang W et al., 2023).

A blend of two biopolymers such as waste fish scale-derived gelatin/sodium alginate presented significantly improved mechanical properties (TS of ≈14 MPa, EAB of ≈45%) compared to the properties of each neat polymer (gelatin film: TS of ≈12 MPa, EAB of ≈17%; sodium alginate film: TS of ≈9 MPa, EAB of ≈24%) (Li et al., 2023). Jiang et al. (2023) developed a citric acid cross-linked chitosan/PVA blend film with good permeability (WVP of 5.26×10^{-4} g h^{-1} m^{-2} Pa^{-1} mm), excellent mechanical properties (TS of ≈16.5 MPa), good creep resistance (EAB of ≈570%), and shape recovery ability (the deformed film can be recovered to 115% of its original size) compared to the film without PVA (WVP of 8.08×10^{-4} g h^{-1} m^{-2} Pa^{-1} mm, TS of ≈7.5, EAB of ~500%). Moreover, the film was applied as packaging for the conservation of fresh cherries stored at room temperature (≈25°C) noting that the film preserved the integrity of the fruit for up to 13 days of storage, while the unpackaged fruit after 7 days of storage already presented a change in color and a wrinkled appearance due to loss of moisture. Similar results were observed in gelatin/chitosan/PVA blend film, where PVA significantly improve the mechanical properties of the film (TS of 32 MPa, EAB of 100%) compared to the properties of the neat gelatin film (TS of 21 MPa, EAB of 5.5%) and gelatin/chitosan blend film (TS of 24 MPa, EAB of 5.7%) (Guo et al., 2023). The bilayer composite based on modified potato starch (purified from waste potato starch) and PLA is other example of a successful polymer blend that presented a drastic improvement of mechanical properties (greater durability, and flexibility), and WVP (14.26×10^{-7} g s^{-1} m^{-1} Pa^{-1}) compared to the biopolymer without PLA (31.69×10^{-7} g s^{-1} m^{-1} Pa^{-1}) (Gürler et al., 2021). A PCL-coated gelatin multilayer film improved the plasticity of the material (EAB of 15.5%), and its WVP (3.3×10^{-10} Kg s^{-1} m^{-2} Pa^{-1}) and oxygen permeability (OP) (8.2×10^{-15} m^3 s^{-1} m^{-2} Pa^{-1}) compared to the neat gelatin film (EAB of 5.83%; WVP of $2{,}290 \times 10^{-10}$ Kg s^{-1} m^{-2} Pa^{-1}; and OP of 13.8×10^{-15} m^3 s^{-1} m^{-2} Pa^{-1}) (Figueroa-Lopez et al., 2018). The addition of crosslinkers, such as gallic acid, improves barrier properties of films based on a blend of corn starch/pullulan (WVP of 4.7×10^{-7} g h^{-1} m^{-1} Pa^{-1}), and mechanical properties (TS of 15.1 MPa, EAB of 64%) compared to the film without the crosslinker (WVP of 9.9×10^{-7} g h^{-1} m^{-1} Pa^{-1}, TS of 18.6 MPa, EAB of 13.3%) (Zhang M et al., 2023). The inclusion of nanoparticles into biopolymers generally improves both permeability and mechanical properties significantly (Wypij et al., 2023). This has been observed with zinc oxide nanoparticles that improved the barrier properties of galactomannan-based films against gasses such as O_2 (0.18 cm^3 mm m^{-2} day^{-1}), a value comparable to PVC plastic (0.7 cm^3 mm m^{-2} day^{-1}), and water vapor (WVP of 2.33×10^{-11} g s^{-1} m^{-1} Pa^{-1}). Moreover, the nanocomposite showed a tensile strength (25–39.8 MPa) very similar to that of HDPE plastic (17 MPa) (Liu et al., 2021). Similar results were observed when zinc oxide nanoparticles were incorporated into carboxymethyl cellulose-based films (Anwar et al., 2022), and chitosan-based films (Basumatary et al., 2023). Silver nanoparticles increased the mechanical properties of chitosan-based films (EAB of 26%, and TS of 26 MPa) compared to the properties of the neat biopolymer film (EAB of 14.8%, and TS of 17 MPa) (El Mouzahim et al., 2023). Xiao et al. (2021) enhanced the mechanical properties, WVP, and OP of soy protein films with cellulose nanocrystals. N-glucose carbon dots significantly improved the oxygen barrier property (OTR of 0.01 cm^3 m^{-2} day^{-1}), without modifying the WVP (0.68×10^{-9} g m s^{-1} m^{-2} Pa^{-1}), and mechanical properties of nanofibrillated cellulose-based films (Ezati et al., 2022). As a last example, lignin nanoparticles, at a concentration between 2% and 3%, increased the TS (48.9 MPa), and elastic modulus (2288.8 MPa) of starch films up to 3.04 times and 2.93 times, respectively, and its OTR was decreased by approximately 50% (Sun et al., 2023).

Despite numerous efforts to obtain a biocomposite material based on proteins and/or polysaccharides with high physical resistance for packaging applications, successful results are usually very few. For this reason, these biocomposites have been applied most successfully as edible preformed material (that would require secondary packaging to guarantee their safety until their final consumption), as edible coating formed on the surface of the product (mainly to extend its shelf life), or as coatings to improve the permeability characteristics of more resistant biodegradable polymeric materials. Some promising developments include the addition of castor oil into guar gum-based films to enhance barrier properties. The developed film effectively decreased the weight loss of mango fruits (by decreasing the rate of moisture loss) when it was applied as a coating on the surface of the product compared to neat guar gum film (Qambrani et al., 2022). Curcumin was incorporated into chitosan-grafted bacterial cellulose films to improve its WVP and OP offering superior preservation of strawberries compared with ordinary PE film (Liu et al., 2021). And searching to improve the functional properties of polymers, it has been possible to effectively demonstrate that WPI films can be used and fabricated on an industrial scale to obtain multilayer pouch systems with mechanical and barrier characteristics of interest to the food industry (Song et al., 2022).

Packaging material plays a key role in the preservation of food safety since, in addition to offering a barrier to protect the product from the external environment, it contributes to inhibiting or preventing product oxidation, and its microbiological deterioration by their activation with functional substances. This last strategy is known as active packaging and will be discussed in the following sections of this study.

5. Biocomposites in active and intelligent packaging: potential uses

Innovative active packaging has emerged as a technology that incorporates compounds that can ensure the quality, safety, and shelf life of packaged food. By incorporating active substances, such as antimicrobials, antioxidants, and oxygen scavengers, this packaging solution actively interacts with the packaged food to maintain its integrity and enhance its overall freshness (Table 1). Biopolymers can interact actively with food components to increase their physicochemical properties and stability. In addition, active packaging protects food against pathogens and decomposition by modifying the phase transitions associated with food quality, without being incorporated into the product formulation (Apicella et al., 2019;

TABLE 1 Recent studies on active and intelligent packaging for food preservation.

Packaging material	Active/intelligent compound	Results	References
Active packaging			
PE and zein	Garlic extract	Reduced the growth of *Penicillium expansum* during storage	Heras-Mozos et al. (2019)
PLA	Kesum	Improved the freshness of chicken meat	Mohamad et al. (2020)
PLA and cyclodextrin	Thymol	Prevented the oxidation of berries	Velázquez-Contreras et al. (2021)
Soy protein films	Cellulose nanocrystals	Reduced the microbial growth in pork meat and extended the shelf life of strawberries	Xiao et al. (2021)
Chitosan and pullulan	Pomegranate peel extract	Increased the shelf life of mango and preserved its phenolic content	Kumar et al. (2021)
Chitosan	Encapsulated *Cinnamodendron dinissi* essential oil	Prevented the oxidation of beef myoglobin	Oliveira Xavier et al. (2021)
Galactomannan	Zinc oxide nanoparticles	Prolong the shelf life of Shine-Muscat grapes	Liu et al. (2021)
Aloe vera gel	Anthocyanin from onion peel	Decrease the weight loss of fig fruits and maintaining the fruit quality	Al-Hilifi et al. (2022)
Xanthan gum	Pomegranate peel extract	Extent the shelf life of mango fruit and maintained the quality	Kumar et al. (2022)
Pullulan and WPC	Citral	Inhibited *Fusarium* in bananas	Iñiguez-Moreno et al. (2022)
Cellulose nanofiber	N-glucose carbon dots	Inhibited the growth of molds in fresh tangerines and strawberries	Ezati et al. (2022)
PVA and starch	Copper oxide and zinc oxide nanoparticles	Extended shelf life of strawberries	Francis et al. (2022)
Chitosan	Tannic acid	Reduced the enzymatic browning of banana and its weight loss, improving its shelf life.	Lee et al. (2023)
Gelatin and sodium alginate	Carvacrol nanoparticles	Maintained the integrity of strawberries and retarded the growth of spoilage microorganisms	Li et al. (2023)
Whey protein and bio-fiber gum	Carvacrol	Reduced the number of *Listeria, E. coli,* and native microorganisms in tomatoes and fresh cut apples	Jin et al. (2023)
PBAT and epoxidized soy bean oil	Lignin and tannic acid	Applied in fresh potato and onion	Olonisakin et al. (2023)
Aloe vera gel	Orange peel essential oil	Extended mushrooms shelf life	Shenbagam et al. (2023)
PVA	Encapsulated *Zataria multiflora* essential oil	Preserved the safety of strawberries	Moradinezhad et al. (2023)
Chitosan	Silver nanoparticles and Kaolin clay	Protect against oxidation of apple slides	El Mouzahim et al. (2023)
Chitosan	Lignin nanoparticles	Retarded the spoilage growth and prevents the oxidation of fish filets.	Zhang W et al. (2023)
Intelligent packaging			
Lallemantia iberica seed gum	Curcumin	Successful detection of shrimp spoilage	Taghinia et al. (2021)
PVA and gelatin	Betalains from *Amaranthus* leaf extract	Increase the shelf life of fish and chicken and monitored correctly the spoilage	Kanatt (2020)
Quaternary ammonium chitosan and gelatin	Betalains from *Amaranthus tricolor* L.	Films suitable to monitor the freshness of shrimps	Hu et al. (2020)
Starch and PVA	Betalains from red pitaya peel extract	Extended the shelf life of shrimps and monitor their freshness	Qin et al. (2020)
Quaternary ammonium chitosan and PVA	Betalains from cactus pears extract	Films sensitive to changes in color with the freshness of the shrimps	Yao et al. (2020)
Chitosan	Anthocyanins from eggplant peels into nanoclays	Great response for monitoring the freshness in round steak stored at different temperatures	Capello et al. (2021)
Soy protein and cellulose nanocrystals	Encapsulated curcumin	Effective visual indicator of shrimp freshness	Xiao et al. (2021)
Cellulose acetate	Pyrano-flavylium salts	Great pH-response in amine-rich environment	Gomes et al. (2022)
Gelatin and *Aloe vera*	Common poppy anthocyanins and rosemary essential oil	Applied for monitoring the freshness of fish filets	Bakhshizadeh et al. (2023)

Baranwal et al., 2022). An even more interesting aspect of this new trend in development materials is that many of the compounds and/or substances used for activation are obtained from other agro-industrial waste, reincorporating it into the value chain, and reducing their negative environmental impact.

The first approach to the application of active packaging lies in the protection of food against oxidation by incorporating natural extracts or essential oils with antioxidant characteristics. PLA films incorporated with essential oils showed efficiency for food packaging. The compatibility between kesum and PLA improved the barrier properties of the film allowing it to preserve the freshness of chicken meat for more than 12 days compared to the neat PLA (Mohamad et al., 2020). Encapsulated thymol in cyclodextrin added into the PLA package had a protective and antioxidant effect on berries, avoiding oxidation after 21 of storage at 4°C and extending their shelf life by one more week, compared to commercial clamshell packaging (Velázquez-Contreras et al., 2021). And fresh potato and onion sealed with a composite film based on PBAT functionalized with epoxidized soybean oil and encapsulated lignin/tannic acid remained fresh for up to 12 days at room temperature (Olonisakin et al., 2023). Among the efficient composites based on biopolymers, the following cases can be mentioned. Composite coatings based on Chitosan/Pullulan or Xanthan gum were supplemented with pomegranate peel extract and applied to mango fruits. Both functionalized composites effectively extend their postharvest shelf life during a storage period of 15–18 days at 22°C and 4°C, compared to the uncoated product whose sensory acceptability did not exceed 12 days of storage (Kumar et al., 2021, 2022). Al-Hilifi et al. (2022) applied *aloe vera* gel-based edible coatings enriched with anthocyanin on fig fruits and observed a clear decrease in the weight loss of the product stored under refrigerated conditions (4°C). The maximum weight loss percentage of the coated product after 12 days of storage was less than 4%, while for the uncoated product, it was greater than 10%. Lee et al. (2023) developed a chitosan film functionalized with 2 wt.% tannic acid which was applied to the packaging of bananas stored under normal ambient conditions in a sunny place. The evaluated film allowed the integrity of the product to be maintained for 7 days with a weight loss of less than 15%, while the unpackaged samples and those packaged with the neat biopolymer did not exceed 3 days of storage without showing enzymatic browning and a weight loss greater than 15% from the third day of storage. Also, nanoencapsulated *Cinnamodendron dinisii* essential oil in zein incorporated into chitosan films prevents the oxidation of beef myoglobin after storage (Oliveira Xavier et al., 2021).

A second very important focus for active packaging is the microbiological preservation of food, which has been achieved through its activation with antimicrobial agents (essential oils, plant extracts, pure bioactive compounds, fillers, or nanoparticles) that delay, reduce, or inhibit microbial growth (Taherimehr et al., 2021). For example, *Zataria multiflora* essential oil encapsulated into a film based on PVA fibers via electrospinning was placed in the lid of PE containers for strawberry storage at 4°C and 85% relative humidity for 15 days. The active biocomposite packaging maintained the integrity and safety of the product during the entire storage time in comparison with the control PE packaging by efficient microbial inhibition (Moradinezhad et al., 2023). Carvacrol incorporated into whey protein and bio-fiber gum composite film improved its CO_2 and O_2 permeability, and reduced the population of *Listeria, E. coli,* and other native microorganisms present in tomatoes and fresh-cut apples after 21 of storage (Jin et al., 2023). A waste fish scale-derived gelatin/sodium based composite film was functionalized with carvacrol nanoparticles (loaded into zeolitic imidazolate framework-8) and applied as a packing film on strawberries. The functionalized film maintained the integrity of the fruit up to 8 days after its storage at room temperature, compared to control materials, including a commercial PE film, in which the product presented microbial infection on the fourth day of storage (Li et al., 2023). Similarly, citral nanoencapsulated in a coating based on pullulan/WPC nanofibers inhibited *Fusarium* infection of bananas, prolonging their shelf life up to 9 days (3 days longer than the uncoated, and coated fruit without citral) at a storage temperature of 25°C (Iñiguez-Moreno et al., 2022). *Aloe vera* gel-based edible coating incorporated with orange peel essential oil was applied on button mushrooms. The coating extended the mushrooms' shelf life when packed in PVC trays and stored in refrigerated conditions (at 4°C with 90% relative humidity) for up to 16 days compared to an uncoated control (12 days) (Shenbagam et al., 2023).

Some nanoparticles have also been incorporated into composites to provide them with mainly antimicrobial functionality. A galactomannan-based nanocomposite film was functionalized with zinc oxide nanoparticles with antimicrobial properties for the packaging of *Shine-Muscat* grapes stored at 25°C with 50% relative humidity. The evaluated packaging presented antimicrobial activity against *E. coli* and *B. subtilis* and prolonged the shelf life of the product (above 5 days compared to a non-functionalized film) by inhibiting the rotting process (Liu et al., 2021). Chitosan films functionalized with silver nanoparticles and Kaolin clay showed efficient antioxidant and antimicrobial properties on *E. coli* and *S. aureus* species. The developed film showed efficient protection against oxidation of apple slices when it was applied as a wrapper and stored at ambient conditions for 24 h (El Mouzahim et al., 2023). PVA/starch composite functionalized with copper oxide and zinc oxide nanoparticles, conferred antimicrobial properties against species of the genus *Aspergillus*, and allowed to maintain the physical and microbiological integrity of strawberries when it was applied as packaging wrapper for its storage at 25°C for 7 days (Francis et al., 2022). Cellulose nanofiber-based films functionalized with N-glucose carbon dots showed antimicrobial activity against the growth of *L. monocytogenes, E. coli*, and *A. flavus*. The studied film was applied as a coating on fresh tangerines and strawberries, allowing it to prolong its shelf life at 25°C, inhibiting the growth mold that compromised the integrity of the uncoated fruits (Ezati et al., 2022). Cellulose nanocrystals enhanced the mechanical properties and water permeability and OP of soy protein films, resulting in the reduction of weight loss and softening of strawberries and delaying the growth of spoilage microorganisms in pork during storage when it was used for its packaging (Xiao et al., 2021). Also, lignin nanoparticles in chitosan-based films retarded the spoilage growth and prevented lipid oxidation of fish filets (Zhang W et al., 2023).

The application of bio-based active coatings is also a promising alternative to improve the efficiency of traditional plastic-based packaging, as it can contribute to increasing the shelf life of a product while reducing waste generation by providing a certain percentage of biodegradability to total packaging material. For example, zein coating activated with garlic extract and bread aroma was applied in PE bags. The developed packaging material extended the shelf life of preservative-free sliced bread loaf by inhibiting the growth of *Penicillium expansum* (up to 25 days more compared to the product stored in uncoated PE bags), and the aroma of bread incorporated into the film masked the sensory perception of the pungency of the garlic extract being acceptable for consumption (Heras-Mozos et al., 2019).

Intelligent materials for food packaging arise from the demand to generate strategies that improve the shelf life of food and also allow the monitoring of product quality in real time (Salgado et al., 2021). Natural compounds have been studied to be incorporated as biological indicators in food packaging materials. Anthocyanins, polyphenols (such as curcumin), and betalains can be used to signal to the consumer of freshness and quality of a food product and to confer antioxidant and antimicrobial properties to the packaging. This is because these compounds are susceptible to changes in physicochemical factors related to the stability of the food, such as pH, producing alterations in their chemical structure that result in color changes (associated with changes in the extent of electron conjugation of its structural chromophore double bonds).

The composition, types, and concentration of these compound groups present and extracted from a particular natural source determine their efficiency as an alternative for this function. Berries are the most common fruits used for the preparation of anthocyanin extracts. However, these are sensitive to light (Neves et al., 2022). Anthocyanins from some extracts have shown better characteristics for this application. For example, anthocyanins from common poppy incorporated into gelatin films/*aloe vera* gel film containing rosemary essential oil functioned effectively as an indicator of the freshness of fish filets placed inside a PET package and stored at room temperature (Bakhshizadeh et al., 2023). Given the limitations and poor stability presented by the anthocyanins in this application, recent studies have focused on pyrano-flavylium salts and anthocyanin-derived pigments. These salts (dye) were incorporated into cellulose acetate-base films conferring the property of change of the film color with increasing concentrations of biogenic amines and ammonia hydroxide which are generally produced during the spoilage of many perishable foods indicating a great potential for its application as a pH freshness indicator in food packaging (Gomes et al., 2022). Another alternative to stabilize anthocyanins is through their absorption on synthetic layered silicate nanoclays. Nanoclays with anthocyanins recovered from agroindustrial waste, such as eggplant peels, have been incorporated into chitosan films, working effectively as a meat freshness monitor at different storage temperatures (4 and 20°C, preferably) (Capello et al., 2021). Curcumin nanoencapsulated incorporated into a soy protein-based film package reinforced with cellulose nanocrystals was able to decrease the total volatile basic N_2 of stored shrimp and worked effectively as a visual indicator of shrimp freshness in real-time during storage (Xiao et al., 2021). Similar successful results in functionality and application were observed when curcumin was incorporated into *Lallemantia iberica* seed gum-based films (Taghinia et al., 2021).

Betalains represent a group of natural pigments that have shown greater efficiency as an indicator in the development of intelligent packaging (Calva-Estrada et al., 2022). For example, the incorporation of betalains extracted from *Amaranthus* into PVA/gelatin films, in addition to conferring antioxidant and antimicrobial properties (against Gram-positive organisms such as *B. cereus*, and *S. aureus* principally) that allows delay oxidation and microbial deterioration of chicken and fish meat, stored at chilled temperature (2–4°C), up to 9 more days compared to non-functionalized film. The packaging proved to have freshness and quality indicator properties for both products, after changing color with the increase in pH, total volatile basic N_2, and microbial spoilage in the samples (Kanatt, 2020). Similar results were observed when betalains from different natural sources (such as amaranth, red pitaya, and cactus pear) were incorporated into quaternary ammonium chitosan/fish gelatin film (Hu et al., 2020), starch/PVA films (Qin et al., 2020), and into quaternary ammonium chitosan/PVA film (Yao et al., 2020) for monitoring the freshness of seafood mainly, such as shrimp and fish meat.

Although many of these alternatives have not been tested in combination with smart devices to enhance the interactive experience with the consumer, these packages were formulated with natural active compounds as anthocyanins, betalains, and curcumin, which may reflect the state of the freshness of the product and indicate through a color change that the food product has deteriorated. However, Chen et al. (2017) did report an improvement in the interaction with the food package by using synthetic pigments that allow monitoring of the spoilage of chicken meat using a smartphone. In the future, smart packaging using natural pigments could be an option to monitor the shelf life and get detailed information about food quality and status of foods using portable devices and other technologies regarding the Fourth Industrial Revolution (4.0 IR).

Integrating biosensors into food packaging materials can allow us to detect the properties of food regarding quality products. As mentioned, intelligent packaging monitors food products using indicators such as freshness indicators using active compounds that change according to the physicochemical and microbiological properties of foods. This packaging could be combined with smart devices connecting to an internet platform for traceability, thus reducing waste and increasing recyclability (Sadeghi et al., 2022; Xu et al., 2023).

The appropriate materials for creating smart biosensor packaging must not only fulfill the requirements for the biomolecule deposition but also meet the standard packing properties as discussed herein. Some of these properties include providing gas barrier properties and vapor or moisture permeability. Typical substrates utilized for intelligent biosensor packaging encompass synthetic plastic polymers, natural polymers, and other diverse materials (Bao et al., 2022). According to Zhang et al. (2021), hydrogels are suitable for included colorimetric biosensors due to their negligible background color and fluorescence emission, carrying capacity, and controllable shape. Also, they provide an inert environment and are an excellent substrate to immobilize materials. In general, the material used to carry a biosensor must be versatile, has to allow the short response of the sensor, is preferably degradable, and is not sensitive to environmental changes inside the package (Wawrzynek et al., 2021).

Plastic films are suitable materials for carrying a biosensor in a food package due to their light weight, flexibility, portability, biocompatibility, and low price. However, as discussed throughout this review, non-degradable polymers such as the polymers commonly used for carrying biosensors must be replaced by biodegradable alternatives. For instance, PET is an outstanding substrate for biosensors due to its high hardness, stiffness, and strength, which support biosensors (Xu et al., 2023). Also, it allows the biosensor to be used as an optical sensor based on PET transparency. However, PLA can also be used to prepare colorimetric biosensitive packages as it displays similar properties to other commodity polymers (Bao et al., 2022). Overall, the type of food packaging material to be used as a carrier for biosensors must have inert properties, lack of color, and carrying capacity.

6. Legislation and worldwide actions toward green packaging

Food packaging is the most prominent industry in plastic consumption and the largest contributor to municipal solid waste. The food packaging market is expected to grow up to 378 billion dollars by 2022 (Zhao et al., 2020). However, biodegradable polymers, set to become the standard of food packaging, only display a market-expected growth of 6 million dollars by 2023 (Baranwal et al., 2022). Awareness of single-use plastics has outpaced private sector practices. Currently, more than 99% of plastic packages are made of non-biodegradable polymers of which 50% are considered single-use plastics (Zhao et al., 2020). Single-use plastics are a major contributor to the global solid waste problem (Walker et al., 2021). Hence, policymakers and stakeholders play a key role in the transition toward a more sustainable plastic paradigm by setting taxation, extending producer responsibility, or banning single-use plastics (Ncube et al., 2021). A virtuous example of successful legislation was the actions taken regarding lightweight plastic bag carriers. Taxation and banning single-use plastic bags in developed countries in Europe have contributed to a drastic reduction in this product consumption. More importantly, the biodegradable or compostable market reacted to these initiatives and nowadays dominates the European market of biodegradable products with over two-thirds of the total market share (Foschi and Bonoli, 2019). A recycling approach was considered by the European Commission by setting targets for 55% of plastic packaging waste prepared for recycling by 2025 and 75% by 2030 (Ncube et al., 2021). Such regulation in cooperation with the European Food Safety Authority has promoted the plastic industry to innovate and invest in recycling plants (Foschi and Bonoli, 2019). Also, Norway has the highest recycling rates of PET due to a redeemable fee charged when purchasing a PET bottle. However, on a global scale, only 9% of the 9 billion tons of plastic were recycled in 2018 and this figure is growing slowly due to the lack of manufacturers' interest in recycling (Ncube et al., 2021).

In this sense, there is a growing concern based on recent research that suggests that several types of plastics are often blended and mixed with other plastic materials during recycling, generating concern about the potential transfer of toxic residues into food if these mixed plastics are melted and used in the food industry. Currently, mechanical recycling is the predominant method used, where washed and sorted plastic waste is reprocessed into new food packaging. However, this recycling process poses certain issues regarding the safe use of recycled plastics in food packaging (De Tandt et al., 2021). One is the challenge of managing waste streams of biopolymers contaminated with petroleum-based plastics or other substances. Inadequate collection and sorting infrastructure often lead to the mixing of biopolymers with conventional plastics during post-consumer disposal. Although advanced sorting technologies like NIR (Near-infrared) spectroscopy and density-based methods can improve separation, they require significant investment (Siddiqui et al., 2021). Hence, from the perspective of a plastics recycler, the legislative requirements and technical barriers for using mechanically recycled plastics in articles placed on the EU market are critical (De Tandt et al., 2021).

To meet these regulations, recyclables face challenges such as ensuring full traceability, preventing potential misuse during their lifetime, and separating food contact materials (FCM) from non-FCM waste. The regulation establishes general requirements for materials or articles intended to come into contact with food. These requirements aim to ensure that substances are inert enough to prevent transfer into food in quantities that could endanger human health or cause undesirable changes in food composition or properties. However, achieving traceability in a post-consumer scenario, except in specific collection schemes like bottle PET via deposit systems, remains highly unlikely. Moreover, the presence of non-intentionally added substances (NIAS) in raw materials used or formed during manufacturing must be considered in FCM risk assessments. When using recycled plastics, additional NIAS may be present due to contamination in the recycled material from previously packaged food, misuse, or the use of additives and their degradation products during recycling (De Tandt et al., 2021).

Learning from PET as a virtuous example of a recycled FCM is essential for the biopolymers market. This polymer offers advantages over other polymers in terms of limited use of chemical additives during conversion, reducing the risk of cross-contaminants in recycled PET (rPET) when properly sorted in waste facilities. Also, the low diffusion rate of chemical substances in PET minimizes the migration of contaminants from packaging to food (Tsochatzis et al., 2022). Moreover, rPET should serve as a model system to explore advanced analytical approaches that validate the safety of its reintegration into value chains (Foschi and Bonoli, 2019). By leveraging state-of-the-art techniques and understanding the safety of rPET, we can further enhance the circularity and sustainability of the food packaging industry.

It is expected that stricter regulations on the use of specific packaging products would stimulate the market to shift to biodegradable, compostable, and alternative packaging materials. However, it is essential to consider whether biopolymers used in food packaging will encounter similar challenges as traditional plastics. While biopolymers offer environmental benefits due to their renewable sources, the risk of blending them with non-food packaging plastics remains, potentially introducing toxic residues into food packaging. When assessing the potential of biopolymers in the food packaging market, it is vital to evaluate the recyclability of different plastics and the economic incentives for recycling them. Particularly for multi-layer food packaging, prioritizing compostable substitutes is important due to the challenges associated with treating and recycling these complex materials, especially considering their potential for contamination as FCM (Kakadellis and Harris, 2020).

By targeting these challenging packaging types, efforts can be directed toward finding sustainable solutions and overcoming the limitations associated with the treatment and recycling of such complex materials. Besides, to ensure the safety of biopolymers, clear legislative requirements, standards, and guidelines should be established. Transparency and traceability within the plastic value chain are also crucial for minimizing contamination risks and maintaining the quality of biopolymer-based food packaging.

Fewer regulations deal with the generation of fully biodegradable packaging materials. The Granting Society with low environmental innovative packaging (GLOPACK) has set a European 2020 action plan set on producing fully biodegradable food trays from biopolymers and agroindustrial waste fibers (Ncube et al., 2020). The R&D sector has dedicated strong efforts to developing packaging solutions for the market. For these to be adopted, they must comply with the regulatory expectations and provide efficiency in food preservation and show no negative impact on food sensory properties. Although for almost a decade, food packaging research has been extensively growing, publishing over 15,000 papers on bio and active packaging technologies, less than 5% of such developments have crossed the gap to reach the market and become exploited patents. Lack of collaboration throughout the supply chain is the main reason hindering efficient lab-scale prototypes to break through in the packaging sector (Guillard et al., 2018).

Governments must acquire a position to finance basic and applied research and adopt policies that demand a sustainable plastic paradigm such as the European Commission Circular Plastic Alliance which envisions 100% of packaging materials to be reusable or recyclable generating zero waste and zero landfilling (Ncube et al., 2021). China was the largest global importer of recycled plastic, but imports ceased since late 2017 causing countries to change their plastic waste management strategies. Canada has successfully implemented an extended producer responsibility (EPR) strategy following the action towards zero plastic waste under the Ocean Plastics Charter by reducing single-use plastics as food packaging waste derived from these materials comprises one-third of the Canadian municipal solid waste, with a very low recovering rate of 20%. EPR programs require all the stakeholders within the supply chain to collaborate, meaning that manufacturers, producers, regulators, consumers, municipalities, educators, and researchers must be accountable for the design of new environmentally friendly packaging materials (Diggle and Walker, 2020). From a consumer perspective, a study carried out in Canada showed that consumers are highly motivated to reduce their consumption of single-use food packaging plastic, but are not willing to pay for sustainable alternatives, for which they are unaware. Consumers play a key role in the supply chain since they dictate market trends through their decision-making. Hence, it is essential to prevent food waste by meeting the technical demands for food packaging while identifying the costs of alternative materials for single-use packaging in the food industry (Walker et al., 2021).

The conventional food packaging paradigm involves linear economies which leads to the depletion of natural resources, greenhouse gas emissions, and generation of solid waste (Ncube et al., 2021). Food waste is associated with plastic pollution because when a food product is thrown away it is usually discarded along with its packaging. In a sustainability assessment of packaged foods, both the product and its packaging should be considered as a single unit with a common environmental footprint, since the same wasted food also contributes to the significant greenhouse gas emission (Crippa et al., 2021; Meherishi et al., 2021). Food packaging constitutes a highly complex system that involves a number of requirements, i.e., formulation, viable production, specific conservation efficiency and functionality, resistance, product quality signaling, a clear composition, and appropriate handling for its final deposition, use, or composting. This ultimately leads to a situation in which talking about sustainable food packaging is a task that requires the active participation of all actors involved: regulatory authorities, food formulators, packaging developers, vendors/distributors, and consumers, in every part of its entire life.

Given this, recent efforts have focused on analyzing a wide variety of unclear, ambiguous, incomplete, and often misapplied definitions related to the sustainability of packaging (including biobased, biodegradable, compostable, eco-friendly, green, recyclable, reusable, circular, among others) to analyze its scope to generate a clear and holistic concept that harmonizes the understanding of the meaning of sustainable packaging. This is how Dörnyei et al. (2023) propose that "sustainable food packaging is an optimized, measured (quantified) and validated solution, which takes into consideration the balance of social, economic, ecological and safe implementations of the circular value chain, based on the entire history (life cycle) of the food product-package unit." This newly proposed concept involves material design considerations (composition, production, thickness, efficiency, handling, biodegradability, composting, etc.) and the integration of awareness and education of its end users that guarantee its correct treatment, disposal, and/or use. Hence, a long journey is planned to achieve the true application of sustainable packaging, based on policies that clarify and regulate the proper use of terms such as "degradable," "oxo-degradable" or "biodegradable" indicated in current packaging that sometimes leads to poor information and communication for the consumer (Din et al., 2020). Official guidelines are required that determine conditions for the evaluation of the biodegradability of new materials for their correct labeling and recognition since different methodologies (ISO, and ASTM) are currently applied in soil conditions, in compost, or in aquatic systems that originate different results for the same biopolymer (Pires et al., 2022). Additionally, meeting these strict conditions requirements in uncontrolled disposal facilities is impossible, thus compromising the biodegradable nature of these packaging materials.

7. Conclusions and perspectives

Single-use plastics in the food packaging industry pose a significant environmental threat, as waste management policies have shown limited success in waste collection and recycling. Biopolymers used for food packaging continue to exhibit numerous deficiencies, encompassing technical, economic, and legislative dimensions. Hence, biopolymers, either synthetic or natural, are a potential solution only when their barrier properties are improved to control the gas composition in the headspace to inhibit aerobic degradation and maintain food integral composition. The exploration of alternative solutions, such as films or composites with a focus on intelligent packaging, is a more favorable avenue since they align well with the principles of sustainable packaging. Moreover, they confer an added advantage by facilitating food preservation and offering indicators of product quality. Several noteworthy alternatives are available, including biopolymers like PLA or PBAT. However, the majority of successful packaging solutions comprise PVA, chitosan, gelatin, or protein-based films. In both scenarios, incorporating essential oils, natural extracts, or nanoparticles into the packaging material has proven effective in enhancing its performance and preserving food throughout its shelf-life. Consequently, prioritizing the development of intelligent alternatives for packaging signifies a more promising trajectory for addressing current limitations and advancing toward an efficient and sustainable packaging system. Although these developments aim to obtain functional and efficient packaging materials in terms of durability, permeability, bioactivity, and conservation, there is a significant research gap in scaling up natural polymer-based packaging materials. Thus, it is necessary to carry out real time packaging tests and to demonstrate real evidence of the feasibility of applying new materials at an industrial level that supports their efficiency under critical storage conditions for the conservation of different food groups.

Author contributions

MG-L, SC-E, and PB-Á: conceptualization and roles/writing—original draft. MG-H and PB-Á: funding acquisition. MG-L, SC-E, MG-H, and PB-Á: investigation. MG-L and MG-H: writing—review and editing. All authors contributed to the article and approved the submitted version.

Funding

Funding for this research was provided by Universidad Panamericana and Tecnológico de Monterrey through the Challenge-Based Research Funding Program.

Acknowledgments

The authors gratefully acknowledge the administrative support of Universidad Panamericana and Tecnológico de Monterrey.

Conflict of interest

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

Publisher's note

References

Alamri, M. S., Qasem, A. A. A., Mohamed, A. A., Hussain, S., Ibraheem, M. A., Shamlan, G., et al. (2021). Food packaging's materials: a food safety perspective. *Saudi J. Biol. Sci.* 28, 4490–4499. doi: 10.1016/J.SJBS.2021.04.047

al-Hilifi, S. A., al-Ali, R. M., al-Ibresam, O. T., Kumar, N., Paidari, S., Trajkovska Petkoska, A., et al. (2022). Physicochemical, morphological, and functional characterization of edible anthocyanin-enriched aloevera coatings on fresh figs (*Ficus carica* L.). *Gels* 8:645. doi: 10.3390/gels8100645

Alias, A. R., Wan, M. K., and Sarbon, N. M. (2022). Emerging materials and technologies of multi-layer film for food packaging application: a review. *Food Control* 136:108875. doi: 10.1016/J.FOODCONT.2022.108875

Ammala, A. (2011). "Nylon-MXD6 resins for food packaging" in *Multifunctional and nanoreinforced polymers for food packaging*. ed. J.-M. Lagarón (Amsterdam: Elsevier), 243–260.

Anwar, M. M., Aly, S. S. H., Nasr, E. H., and El-Sayed, E. S. R. (2022). Improving carboxymethyl cellulose edible coating using ZnO nanoparticles from irradiated a lternaria tenuissima. *AMB Express* 12:116. doi: 10.1186/s13568-022-01459-x

Apicella, A., Scarfato, P., Di Maio, L., and Incarnato, L. (2019). Sustainable active PET films by functionalization with antimicrobial bio-coatings. *Front. Mater.* 6:243. doi: 10.3389/fmats.2019.00243

Aragón-Gutierrez, A., Arrieta, M. P., López-González, M., Fernández-García, M., and López, D. (2020). Hybrid biocomposites based on poly(lactic acid) and silica aerogel for food packaging applications. *Materials* 13, 1–18. doi: 10.3390/ma13214910

Asgher, M., Qamar, S. A., Bilal, M., and Iqbal, H. M. N. (2020). Bio-based active food packaging materials: sustainable alternative to conventional petrochemical-based packaging materials. *Food Res. Int.* 137:109625. doi: 10.1016/j.foodres.2020.109625

Azhar Shapawi, Z. I., Ariffin, S. H., Shamsudin, R., ISMA, T., and Gkatzionis, K. (2021). Modeling respiration rate of fresh-cut sweet potato (Anggun) stored in different packaging films. *Food Packag. Shelf Life* 28:100657. doi: 10.1016/j.fpsl.2021.100657

Aznar, M., Domeño, C., Nerín, C., and Bosetti, O. (2015). Set-off of non-volatile compounds from printing inks in food packaging materials and the role of lacquers to avoid migration. *Dyes Pigments* 114, 85–92. doi: 10.1016/J.DYEPIG.2014.10.019

Bakhshizadeh, M., Ayaseh, A., Hamishehkar, H., Kaal, H. S., Moghaddam, T. N., Haghi, P. B., et al. (2023). Designing a multifunctional packaging system based on gelatin/alove vera gel film containing of rosemary essential oil and common poppy anthocyanins. *Res Sq.* doi: 10.21203/rs.3.rs-2508080/v1

Balaguer, M. P., Lopez-Carballo, G., Catala, R., Gavara, R., and Hernandez-Munoz, P. (2013). Antifungal properties of gliadin films incorporating cinnamaldehyde and application in active food packaging of bread and cheese spread foodstuffs. *Int. J. Food Microbiol.* 166, 369–377. doi: 10.1016/J.IJFOODMICRO.2013.08.012

Bao, F., Liang, Z., Deng, J., Lin, Q., Li, W., Peng, Q., et al. (2022). Toward intelligent food packaging of biosensor and film substrate for monitoring foodborne microorganisms: a review of recent advancements. *Crit. Rev. Food Sci. Nutr.*, 1–12. doi: 10.1080/10408398.2022.2137774 [In Press].

Baranwal, J., Barse, B., Fais, A., Delogu, G. L., and Kumar, A. (2022). Biopolymer: a sustainable material for food and medical applications. *Polymers (Basel)* 14:983. doi: 10.3390/polym14050983

Barrett, D. M., Beaulieu, J. C., and Shewfelt, R. (2010). Color, flavor, texture, and nutritional quality of fresh-cut fruits and vegetables: desirable levels, instrumental and sensory measurement, and the effects of processing. *Crit. Rev. Food Sci. Nutr.* 50, 369–389. doi: 10.1080/10408391003626322

Basumatary, I. B., Mukherjee, A., and Kumar, S. (2023). Chitosan-based composite films containing eugenol nanoemulsion, ZnO nanoparticles and *Aloe vera* gel for active food packaging. *Int. J. Biol. Macromol.* 242:124826. doi: 10.1016/j.ijbiomac.2023.124826

Battisti, R., Fronza, N., Vargas Júnior, Á., Silveira, S. M.Da, Damas, M. S. P., and Quadri, M. G. N. (2017). Gelatin-coated paper with antimicrobial and antioxidant effect for beef packaging. *Food Packag. Shelf Life* 11, 115–124. doi:10.1016/J.FPSL.2017.01.009

Bhargava, N., Sharanagat, V. S., Mor, R. S., and Kumar, K. (2020). Active and intelligent biodegradable packaging films using food and food waste-derived bioactive compounds: a review. *Trends Food Sci. Technol.* 105, 385–401. doi: 10.1016/J.TIFS.2020.09.015

Bradley, E. L., Stratton, J. S., Leak, J., Lister, L., and Castle, L. (2013). Printing ink compounds in foods: UK survey results. *Food Addit. Contam. Part B* 6, 73–83. doi: 10.1080/19393210.2012.725774

Bugnicourt, E., Schmid, M., Nerney, O. M., Wildner, J., Smykala, L., Lazzeri, A., et al. (2013). Processing and validation of whey-protein-coated films and laminates at semi-industrial scale as novel recyclable food packaging materials with excellent barrier properties. *Adv. Mater. Sci. Eng.* 2013, 1–10. doi: 10.1155/2013/496207

Bumbudsanpharoke, N., Wongphan, P., Promhuad, K., Leelaphiwat, P., and Harnkarnsujarit, N. (2022). Morphology and permeability of bio-based poly(butylene adipate-co-terephthalate) (PBAT), poly(butylene succinate) (PBS) and linear low-density polyethylene (LLDPE) blend films control shelf-life of packaged bread. *Food Control* 132:108541. doi: 10.1016/J.FOODCONT.2021.108541

Calva-Estrada, S. J., Jiménez-Fernández, M., and Lugo-Cervantes, E. (2022). Betalains and their applications in food: the current state of processing, stability and future opportunities in the industry. *Food Chem. Mol. Sci.* 4:100089. doi: 10.1016/J.FOCHMS.2022.100089

Calva-Estrada, S. J., Jimenez-Fernandez, M., Vallejo-Cardona, A. A., Castillo-Herrera, G. A., and Lugo-Cervantes, E. D. C. (2021). Cocoa nanoparticles to improve the physicochemical and functional properties of whey protein-based films to extend the shelf life of muffins. *Foods* 10:2672. doi: 10.3390/foods10112672

Capello, C., Leandro, G. C., Gagliardi, T. R., and Valencia, G. A. (2021). Intelligent films from chitosan and biohybrids based on anthocyanins and Laponite®: physicochemical properties and food packaging applications. *J. Polym. Environ.* 29, 3988–3999. doi: 10.1007/s10924-021-02168-5

Cazón, P., and Vázquez, M. (2021). Bacterial cellulose as a biodegradable food packaging material: a review. *Food Hydrocoll.* 113:106530. doi: 10.1016/j.foodhyd.2020.106530

Cazón, P., Velazquez, G., Ramírez, J. A., and Vázquez, M. (2017). Polysaccharide-based films and coatings for food packaging: a review. *Food Hydrocoll.* 68, 136–148. doi: 10.1016/j.foodhyd.2016.09.009

Chaliha, M., Cusack, A., Currie, M., Sultanbawa, Y., and Smyth, H. (2013). Effect of packaging materials and storage on major volatile compounds in three Australian native herbs. *J. Agric. Food Chem.* 61, 5738–5745. doi: 10.1021/jf400845t

Chang, X., Hou, Y., Liu, Q., Hu, Z., Xie, Q., Shan, Y., et al. (2021). Physicochemical and antimicrobial properties of chitosan composite films incorporated with glycerol monolaurate and nano-TiO2. *Food Hydrocoll.* 119:106846. doi: 10.1016/j.foodhyd.2021.106846

Channa, I. A., Ashfaq, J., Gilani, S. J., Chandio, A. D., Yousuf, S., Makhdoom, M. A., et al. (2022). Sustainable and eco-friendly packaging films based on poly (vinyl alcohol) and glass flakes. *Membranes (Basel)* 12:701. doi: 10.3390/membranes12070701

Chen, Y., Fu, G., Zilberman, Y., Ruan, W., Ameri, S. K., Zhang, Y. S., et al. (2017). Low cost smart phone diagnostics for food using paper-based colorimetric sensor arrays. *Food Control* 82, 227–232. doi: 10.1016/J.FOODCONT.2017.07.003

Chen, J., Hu, Y., Yan, R., Hu, H., Chen, Y., and Zhang, N. (2019). Modeling the dynamic changes in O2 and CO2 concentrations in MAP-packaged fresh-cut garlic scapes. *Food Packag. Shelf Life* 22:100432. doi: 10.1016/j.fpsl.2019.100432

Chen, L., and Opara, U. L. (2013). Texture hmeasurement approaches in fresh and processed foods – a review. *Food Res. Int.* 51, 823–835. doi: 10.1016/j.foodres.2013.01.046

Cheng, H., Xu, H., Julian McClements, D., Chen, L., Jiao, A., Tian, Y., et al. (2022). Recent advances in intelligent food packaging materials: principles, preparation and applications. *Food Chem.* 375:131738. doi: 10.1016/j.foodchem.2021.131738

Chin, K. M., Sam, S. T., Ong, H. L., Wong, Y. S., Tan, W. K., and Vannaladsaysy, V. (2022). Bioinspired crosslinked nanocomposites of polyvinyl alcohol-reinforced cellulose nanocrystals extracted from rice straw with ethanedioic acid. *J. Nanomater.* 2022, 1–16. doi: 10.1155/2022/3225211

Cinelli, P., Schmid, M., Bugnicourt, E., Wildner, J., Bazzichi, A., Anguillesi, I., et al. (2014). Whey protein layer applied on biodegradable packaging film to improve barrier properties while maintaining biodegradability. *Polym. Degrad. Stab.* 108, 151–157. doi: 10.1016/J.POLYMDEGRADSTAB. 2014.07.007

Craster, B., and Jones, T. G. J. (2019). Permeation of a range of species through polymer layers under varying conditions of temperature and pressure: in situ measurement methods. *Polymers (Basel)* 11:1056. doi: 10.3390/polym11061056

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., and Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat Food* 2, 198–209. doi: 10.1038/s43016-021-00225-9

Daniloski, D., Petkoska, A. T., Galić, K., Ščetar, M., Kurek, M., Vaskoska, R., et al. (2019). The effect of barrier properties of polymeric films on the shelf-life of vacuum packaged fresh pork meat. *Meat Sci.* 158:107880. doi: 10.1016/j.meatsci.2019.107880

De Tandt, E., Demuytere, C., Van Asbroeck, E., Moerman, H., Mys, N., Vyncke, G., et al. (2021). A recycler's perspective on the implications of REACH and food contact material (FCM) regulations for the mechanical recycling of FCM plastics. *Waste Manag.* 119, 315–329. doi: 10.1016/j.wasman.2020.10.012

Diggle, A., and Walker, T. R. (2020). Implementation of harmonized extended producer responsibility strategies to incentivize recovery of single-use plastic packaging waste in Canada. *Waste Manag.* 110, 20–23. doi: 10.1016/J.WASMAN.2020.05.013

Din, M. I., Ghaffar, T., Najeeb, J., Hussain, Z., Khalid, R., and Zahid, H. (2020). Potential perspectives of biodegradable plastics for food packaging application-review of properties and recent developments. *Food Addit. Contam. Part A Chem. Anal. Control Expo. Risk Assess.* 37, 665–680. doi: 10.1080/19440049.2020.1718219

Dörnyei, K. R., Uysal-Unalan, I., Krauter, V., Weinrich, R., Incarnato, L., Karlovits, I., et al. (2023). Sustainable food packaging: an updated definition following a holistic approach. *Front. Sustain. Food Syst.* 7:1119052. doi: 10.3389/fsufs.2023.1119052

Efthymiou, M. N., Tsouko, E., Papagiannopoulos, A., Athanasoulia, I. G., Georgiadou, M., Pispas, S., et al. (2022). Development of biodegradable films using sunflower protein isolates and bacterial nanocellulose as innovative food packaging materials for fresh fruit preservation. *Sci. Rep.* 12:6935. doi: 10.1038/s41598-022-10913-6

El Mouzahim, M., Eddarai, E. M., Eladaoui, S., Guenbour, A., Bellaouchou, A., Zarrouk, A., et al. (2023). Effect of kaolin clay and *Ficus carica* mediated silver nanoparticles on chitosan food packaging film for fresh apple slice preservation. *Food Chem.* 410:135470. doi: 10.1016/j.foodchem.2023.135470

Ezati, P., Rhim, J. W., Molaei, R., Priyadarshi, R., and Han, S. (2022). Cellulose nanofiber-based coating film integrated with nitrogen-functionalized carbon dots for active packaging applications of fresh fruit. *Postharvest Biol. Technol.* 186:111845. doi: 10.1016/j.postharvbio.2022.111845

Fabra, M. J., Hambleton, A., Talens, P., Debeaufort, F., Chiralt, A., and Voilley, A. (2008). Aroma barrier properties of sodium caseinate-based films. *Biomacromolecules* 9, 1406–1410. doi: 10.1021/BM701363P/ASSET/IMAGES/MEDIUM/BM-2007-01363P_0006.GIF

Figueroa-Lopez, K. J., Castro-Mayorga, J. L., Andrade-Mahecha, M. M., Cabedo, L., and Lagaron, J. M. (2018). Antibacterial and barrier properties of gelatin coated by electrospun polycaprolactone ultrathin fibers containing black pepper oleoresin of interest in active food biopackaging applications. *Nano* 8:199. doi: 10.3390/nano8040199

Foschi, E., and Bonoli, A. (2019). The commitment of packaging industry in the framework of the European strategy for plastics in a circular economy. *Adm Sci* 9:18. doi: 10.3390/admsci9010018

Francis, D. V., Thaliyakattil, S., Cherian, L., Sood, N., and Gokhale, T. (2022). Metallic nanoparticle integrated ternary polymer blend of PVA/starch/glycerol: a promising antimicrobial food packaging material. *Polymers (Basel)* 14:1379. doi: 10.3390/polym14071379

Fredi, G., and Dorigato, A. (2021). Recycling of bioplastic waste: a review. *Adv. Ind. Eng. Polym. Res.* 4, 159–177. doi: 10.1016/J.AIEPR.2021.06.006

Gomes, V., Pires, A. S., Mateus, N., de Freitas, V., and Cruz, L. (2022). Pyranoflavylium-cellulose acetate films and the glycerol effect towards the development of pH-freshness smart label for food packaging. *Food Hydrocoll.* 127:107501. doi: 10.1016/j.foodhyd.2022.107501

Guidotti, G., Soccio, M., Lotti, N., Siracusa, V., Gazzano, M., and Munari, A. (2019). New multi-block copolyester of 2,5-furandicarboxylic acid containing PEG-like sequences to form flexible and degradable films for sustainable packaging. *Polym. Degrad. Stab.* 169:108963. doi: 10.1016/j.polymdegradstab.2019.108963

Guillard, V., Gaucel, S., Fornaciari, C., Angellier-Coussy, H., Buche, P., and Gontard, N. (2018). The next generation of sustainable food packaging to preserve our environment in a circular economy context. *Front. Nutr.* 5:121. doi: 10.3389/fnut.2018.00121

Guo, H., Shao, C., Ma, Y., Zhang, Y., and Lu, P. (2023). Development of active and intelligent pH food packaging composite films incorporated with litchi shell extract as an indicator. *Int. J. Biol. Macromol.* 226, 77–89. doi: 10.1016/j.ijbiomac.2022.11.325

Gürler, N., Paşa, S., and Temel, H. (2021). Silane doped biodegradable starch-PLA bilayer films for food packaging applications: mechanical, thermal, barrier and biodegradability properties. *J. Taiwan Inst. Chem. Eng.* 123, 261–271. doi: 10.1016/j.jtice.2021.05.030

Hakim, L., Kumar, L., and Gaikwad, K. K. (2023). Screen printing of catechu (Senegalia catechu)/guar gum based edible ink for food printing and packaging applications. *Prog. Org. Coat.* 182:107629. doi: 10.1016/j.porgcoat.2023.107629

Heras-Mozos, R., Muriel-Galet, V., López-Carballo, G., Catalá, R., Hernández-Muñoz, P., and Gavara, R. (2019). Development and optimization of antifungal packaging for sliced pan loaf based on garlic as active agent and bread aroma as aroma corrector. *Int. J. Food Microbiol.* 290, 42–48. doi: 10.1016/j.ijfoodmicro.2018.09.024

Horman, S., Laorenza, Y., Behzadfar, E., Sonchaeng, U., Wadaugsorn, K., Sodsai, J., et al. (2022). Functional polymer and packaging technology for bakery products. *Polymers (Basel)* 14:3793. doi: 10.3390/polym14183793

Hu, H., Yao, X., Qin, Y., Yong, H., and Liu, J. (2020). Development of multifunctional food packaging by incorporating betalains from vegetable amaranth (*Amaranthus tricolor* L.) into quaternary ammonium chitosan/fish gelatin blend films. *Int. J. Biol. Macromol.* 159, 675–684. doi: 10.1016/J.IJBIOMAC.2020.05.103

Hutchings, N., Smyth, B., Cunningham, E., and Mangwandi, C. (2021). Development of a mathematical model to predict the growth of pseudomonas spp. in, and film permeability requirements of, high oxygen modified atmosphere packaging for red meat. *J. Food Eng.* 289:110251. doi: 10.1016/j.jfoodeng.2020.110251

Iglesias Montes, M. L., Luzi, F., Dominici, F., Torre, L., Cyras, V. P., Manfredi, L. B., et al. (2019). Design and characterization of PLA bilayer films containing lignin and cellulose nanostructures in combination with umbelliferone as active ingredient. *Front. Chem.* 7:157. doi: 10.3389/FCHEM.2019.00157/BIBTEX

Iñiguez-Moreno, M., Calderón-Santoyo, M., Barros-Castillo, J. C., Miss-Zacarías, D. M., Díaz, J. A., and Ragazzo-Sánchez, J. A. (2022). Nanofibers added with citral: characterization and their application to postharvest control of fusarium pseudocircinatum in bananas. *J. Food Process. Preserv.* 46:e17188. doi: 10.1111/jfpp.17188

Jiang, S., Qiao, C., Liu, R., Liu, Q., Xu, J., and Yao, J. (2023). Structure and properties of citric acid cross-linked chitosan/poly(vinyl alcohol) composite films for food packaging applications. *Carbohydr. Polym.* 312:120842. doi: 10.1016/j.carbpol.2023.120842

Jin, T. Z., Yadav, M. P., and Qi, P. X. (2023). Antimicrobial and physiochemical properties of films and coatings prepared from bio-fiber gum and whey protein isolate conjugates. *Food Control* 148:109666. doi: 10.1016/j.foodcont.2023.109666

Kaewprachu, P., Osako, K., Benjakul, S., Suthiluk, P., and Rawdkuen, S. (2017). Shelf life extension for Bluefin tuna slices (*Thunnus thynnus*) wrapped with myofibrillar protein film incorporated with catechin-Kradon extract. *Food Control* 79, 333–343. doi: 10.1016/J.FOODCONT.2017.04.014

Kakadellis, S., and Harris, Z. M. (2020). Don't scrap the waste: the need for broader system boundaries in bioplastic food packaging life-cycle assessment – a critical review. *J. Clean. Prod.* 274:122831. doi: 10.1016/j.jclepro.2020.122831

Kanatt, S. R. (2020). Development of active/intelligent food packaging film containing amaranthus leaf extract for shelf life extension of chicken/fish during chilled storage. *Food Packag. Shelf Life* 24:100506. doi: 10.1016/j.fpsl.2020.100506

Kazemi, M., Jahanbin, K., Ojagh, S. M., and Abdollahi, M. (2023). Development of antimicrobial gelatin-ulvan-beeswax composite films: optimization of formulation using mixture design methodology. *Int. J. Biol. Macromol.* 231:123384. doi: 10.1016/j.ijbiomac.2023.123384

Kumar, N., Pratibha, N., Petkoska, A. T., Al-Hilifi, S. A., and Fawole, O. A. (2021). Effect of chitosan–pullulan composite edible coating functionalized with pomegranate peel extract on the shelf life of mango (*Mangifera indica*). *Coatings* 11:764. doi: 10.3390/coatings11070764

Kumar, L., Ramakanth, D., Akhila, K., and Gaikwad, K. K. (2022). Edible films and coatings for food packaging applications: a review. *Environ. Chem. Lett.* 20, 875–900. doi: 10.1007/s10311-021-01339-z

Lara-Topete, G. O., Yebra-Montes, C., Orozco-Nunnelly, D. A., Robles-Rodríguez, C. E., and Gradilla-Hernández, M. S. (2022). An integrated environmental assessment of MSW management in a large city of a developing country: taking the first steps towards a circular economy model. *Front. Environ. Sci.* 10:327. doi: 10.3389/FENVS.2022.838542/BIBTEX

Lawal, U., Samyuktha, R., Robert, V., Sreelakshmi, K., Gopi, A., Poochi, M., et al. (2023). Poly(lactic acid)/cholecalciferol based composites for active food packaging application. *Int. J. Biol. Macromol.* 246:125637. doi: 10.1016/j.ijbiomac.2023.125637

Lee, S. J., Gwak, M. A., Chathuranga, K., Lee, J. S., Koo, J., and Park, W. H. (2023). Multifunctional chitosan/tannic acid composite films with improved anti-UV, antioxidant, and antimicrobial properties for active food packaging. *Food Hydrocoll.* 136:108249. doi: 10.1016/j.foodhyd.2022.108249

Lee, D. S., Wang, H. J., Jaisan, C., and An, D. S. (2022). Active food packaging to control carbon dioxide. *Packag. Technol. Sci.* 35, 213–227. doi: 10.1002/pts.2627

Li, Y., Shan, P., Yu, F., Li, H., and Peng, L. (2023). Fabrication and characterization of waste fish scale-derived gelatin/sodium alginate/carvacrol loaded ZIF-8 nanoparticles composite films with sustained antibacterial activity for active food packaging. *Int. J. Biol. Macromol.* 230:123192. doi: 10.1016/j.ijbiomac.2023.123192

Li, N., Zhou, Z., Wu, F., Lu, Y., Jiang, D., Zhong, L., et al. (2022). Development of pH-indicative and antimicrobial films based on polyvinyl alcohol/starch incorporated with ethyl lauroyl arginate and mulberry anthocyanin for active packaging. *Coatings* 12:1392. doi: 10.3390/coatings12101392

Liu, R., and Mabury, S. A. (2021). Printing ink related chemicals, including synthetic phenolic antioxidants, organophosphite antioxidants, and photoinitiators, in printing paper products and implications for human exposure. *Environ. Int.* 149:106412. doi: 10.1016/J.ENVINT.2021.106412

Liu, W., Wang, T., Tao, Y., Ling, Z., Huang, C., Lai, C., et al. (2021). Fabrication of anti-bacterial, hydrophobic and UV resistant galactomannan-zinc oxide nanocomposite films. *Polymer (Guildf)* 215:123412. doi: 10.1016/j.polymer.2021.123412

Manikandan, N. A., Pakshirajan, K., and Pugazhenthi, G. (2020). Preparation and characterization of environmentally safe and highly biodegradable microbial polyhydroxybutyrate (PHB) based graphene nanocomposites for potential food packaging applications. *Int. J. Biol. Macromol.* 154, 866–877. doi: 10.1016/j.ijbiomac.2020.03.084

Mariño-Cortegoso, S., Stanzione, M., Andrade, M. A., Restuccia, C., Rodríguez-Bernaldo de Quirós, A., Buonocore, G. G., et al. (2022). Development of active films utilizing antioxidant compounds obtained from tomato and lemon by-products for use in food packaging. *Food Control* 140:109128. doi: 10.1016/j.foodcont.2022.109128

Meherishi, L., Narayana, S. A., and Ranjani, K. S. (2021). Integrated product and packaging decisions with secondary packaging returns and protective packaging management. *Eur. J. Oper. Res.* 292, 930–952. doi: 10.1016/J.EJOR.2020.11.022

Miranda, G., Berna, A., and Mulet, A. (2019). Dried-fruit storage: an analysis of package headspace atmosphere changes. *Foods* 8:56. doi: 10.3390/foods8020056

Modi, B., Timilsina, H., Bhandari, S., Achhami, A., Pakka, S., Shrestha, P., et al. (2021). Current trends of food analysis, safety, and packaging. *Int. J. Food Sci.* 2021, 1–20. doi: 10.1155/2021/9924667

Mohamad, N., Mazlan, M. M., Tawakkal, I. S. M. A., Talib, R. A., Kian, L. K., Fouad, H., et al. (2020). Development of active agents filled polylactic acid films for food packaging application. *Int. J. Biol. Macromol.* 163, 1451–1457. doi: 10.1016/j.ijbiomac.2020.07.209

Mohebbi, M., Ansarifar, E., Hasanpour, N., and Amiryousefi, M. R. (2012). Suitability of aloe vera and gum tragacanth as edible coatings for extending the shelf life of button mushroom. *Food Bioprocess Technol.* 5, 3193–3202. doi: 10.1007/s11947-011-0709-1

Moradinezhad, F., Hedayati, S., and Ansarifar, E. (2023). Assessment of zataria multiflora essential oil—incorporated electrospun polyvinyl alcohol Fiber mat as active packaging. *Polymers (Basel)* 15:1048. doi: 10.3390/polym15041048

Mousavi Khaneghah, A., Hashemi, S. M. B., and Limbo, S. (2018). Antimicrobial agents and packaging systems in antimicrobial active food packaging: an overview of approaches and interactions. *Food Bioprod. Process.* 111, 1–19. doi:10.1016/j.fbp.2018.05.001, 1.

Nazrin, A., Sapuan, S. M., Zuhri, M. Y. M., Ilyas, R. A., Syafiq, R., and Sherwani, S. F. K. (2020). Nanocellulose reinforced thermoplastic starch (TPS), polylactic acid (PLA), and polybutylene succinate (PBS) for food packaging applications. *Front. Chem.* 8:213. doi: 10.3389/fchem.2020.00213

Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., and Beas, I. N. (2020). Environmental impact of food packaging materials: a review of contemporary development from conventional plastics to polylactic acid based materials. *Materials* 13, 1–24. doi: 10.3390/ma13214994

Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., and Beas, I. N. (2021). An overview of plasticwaste generation and management in food packaging industries. *Recycling* 6, 1–25. doi: 10.3390/recycling6010012

Neves, D., Andrade, P. B., Videira, R. A., de Freitas, V., and Cruz, L. (2022). Berry anthocyanin-based films in smart food packaging: a mini-review. *Food Hydrocoll.* 133:107885. doi: 10.1016/j.foodhyd.2022.107885

Oliveira Xavier, L., Sganzerla, W. G., Bachega Rosa, G., Gonçalves da Rosa, C., Agostinetto, L., de Lima Veeck, A. P., et al. (2021). Chitosan packaging functionalized with cinnamodendron dinisii essential oil loaded zein: a proposal for meat conservation. *Int. J. Biol. Macromol.* 169, 183–193. doi: 10.1016/j.ijbiomac.2020.12.093

Olonisakin, K., Wen, A., He, S., Lin, H., Tao, W., Chen, S., et al. (2023). The development of biodegradable PBAT-lignin-tannic acid composite film: properties, biodegradability, and potential barrier application in food packaging. *Food Bioprocess Technol.* 16, 1525–1540. doi: 10.1007/s11947-023-02997-3

Onyeaka, H. N., and Nwabor, O. F. (2022). "Natural polymers as food packaging materials" in *Food preservation and safety of natural products*. eds. H. N. Onyeaka and O. F. Nwabor (Cambridge, MA: Academic Press), 133–145.

Ozcan, A., and Arman Kandirmaz, E. (2020). Natural ink production and printability studies for smart food packaging. *Color. Res. Appl.* 45, 495–502. doi: 10.1002/col.22488

Ozdemir, M., and Floros, J. D. (2004). Active food packaging technologies. *Crit. Rev. Food Sci. Nutr.* 44, 185–193. doi: 10.1080/10408690490441578

Pérez-Fonseca, A. A., González-López, M. E., and Robledo-Ortíz, J. R. (2023). Reprocessing and recycling of poly(lactic acid): a review. *J. Polym. Environ.* 2023, 1–17. doi: 10.1007/S10924-023-02919-6

Phothisarattana, D., Wongphan, P., Promhuad, K., Promsorn, J., and Harnkarnsujarit, N. (2021). Biodegradable poly(butylene Adipate-co-terephthalate) and thermoplastic starch-blended TiO 2 nanocomposite blown films as functional active packaging of fresh fruit. *Polymers (Basel)* 13:4192. doi: 10.3390/polym13234192

Pires, J. R. A., Souza, V. G. L., Fuciños, P., Pastrana, L., and Fernando, A. L. (2022). Methodologies to assess the biodegradability of bio-based polymers—current knowledge and existing gaps. *Polymers (Basel)* 14:1359. doi: 10.3390/polym14071359

Popović, S., Peričin, D., Vaštag, Ž., Lazić, V., and Popović, L. (2012). Pumpkin oil cake protein isolate films as potential gas barrier coating. *J. Food Eng.* 110, 374–379. doi: 10.1016/J.JFOODENG.2011.12.035

Porta, R., Sabbah, M., and Di Pierro, P. (2020). Biopolymers as food packaging materials. *Int. J. Mol. Sci.* 21, 1–3. doi: 10.3390/ijms21144942

Prasad, J., Dixit, A., Sharma, S. P., Mwakosya, A. W., Petkoska, A. T., Upadhyay, A., et al. (2024). Nanoemulsion-based active packaging for food products. *Foods Raw Mater.* 12, 22–36. doi: 10.21603/2308-4057-2024-1-585

Qambrani, S., Talpur, F. N., Panhwar, A. A., Afridi, H. I., Talpur, M. K., Khan, A., et al. (2022). Development of guar gum-based coating with castor oil for improved postharvest quality of fresh mangoes using response surface methodology. *Appl. Food Res.* 2:100220. doi: 10.1016/j.afres.2022.100220

Qin, Y., Liu, Y., Zhang, X., and Liu, J. (2020). Development of active and intelligent packaging by incorporating betalains from red pitaya (*Hylocereus polyrhizus*) peel into starch/polyvinyl alcohol films. *Food Hydrocoll.* 100:105410. doi: 10.1016/J.FOODHYD.2019.105410

Rekhi, P., Goswami, M., Ramakrishna, S., and Debnath, M. (2022). Polyhydroxyalkanoates biopolymers toward decarbonizing economy and sustainable future. *Crit. Rev. Biotechnol.* 42, 668–692. doi: 10.1080/07388551.2021.1960265

Rodríguez-Rojas, A., Arango Ospina, A., Rodríguez-Vélez, P., and Arana-Florez, R. (2019). ¿what is the new about food packaging material? A bibliometric review during 1996–2016. *Trends Food Sci. Technol.* 85, 252–261. doi: 10.1016/j.tifs.2019.01.016

Romero, C., Brenes, M., García-Serrano, P., Medina, E., and García-García, P. (2019). Packing black ripe olives in retortable pouches with different oxygen permeability. *Food Packag. Shelf Life* 20:100323. doi: 10.1016/j.fpsl.2019.100323

Rossi Marquez, G., Di Pierro, P., Esposito, M., Mariniello, L., and Porta, R. (2014). Application of transglutaminase-crosslinked whey protein/pectin films as water barrier coatings in fried and baked foods. *Food Bioprocess Technol.* 7, 447–455. doi: 10.1007/s11947-012-1045-9

Sadeghi, K., Kim, J., and Seo, J. (2022). Packaging 4.0: the threshold of an intelligent approach. *Compr. Rev. Food Sci. Food Saf.* 21, 2615–2638. doi: 10.1111/1541-4337.12932

Salehi, A., Jafari, S. H., Khonakdar, H. A., and Ebadi-Dehaghani, H. (2018). Temperature dependency of gas barrier properties of biodegradable PP/PLA/nanoclay films: experimental analyses with a molecular dynamics simulation approach. *J. Appl. Polym. Sci.* 135:46665. doi: 10.1002/app.46665

Salgado, P. R., Di Giorgio, L., Musso, Y. S., and Mauri, A. N. (2021). Recent developments in smart food packaging focused on biobased and biodegradable polymers. *Front. Sustain Food Syst.* 5:630393. doi: 10.3389/fsufs.2021.630393

Sánchez-Gutiérrez, M., Bascón-Villegas, I., Espinosa, E., Carrasco, E., Pérez-Rodríguez, F., and Rodríguez, A. (2021). Cellulose nanofibers from olive tree pruning as food packaging additive of a biodegradable film. *Foods* 10:1584. doi: 10.3390/foods10071584

Scarsella, J. B., Zhang, N., and Hartman, T. G. (2019). Identification and migration studies of photolytic decomposition products of UV-photoinitiators in food packaging. *Molecules* 24:3592. doi: 10.3390/MOLECULES24193592

Seyfzadeh, M., Motalebi, A. A., Kakoolaki, S., and Gholipour, H. (2013). Chemical, microbiological and sensory evaluation of gutted kilka coated with whey protein based edible film incorporated with sodium alginate during frozen storage. *Iran. J. Fish. Sci.* 12, 140–153.

Shenbagam, A., Kumar, N., Rahul, K., Upadhyay, A., Gniewosz, M., and Kieliszek, M. (2023). Characterization of *Aloe Vera* gel-based edible coating with orange peel essential oil and its preservation effects on button mushroom (Agaricus bisporus). *Food Bioprocess Technol.*, 1–21. doi: 10.1007/s11947-023-03107-z [In Press].

Siddiqui, M. N., Redhwi, H. H., Al-Arfaj, A. A., and Achilias, D. S. (2021). Chemical recycling of pet in the presence of the bio-based polymers, pla, phb and pef: a review. *Sustainability (Switzerland)* 13:10528. doi: 10.3390/su131910528

Singh, B., Suri, K., Shevkani, K., Kaur, A., Kaur, A., and Singh, N. (2018). "Enzymatic browning of fruit and vegetables: a review" in *Enzymes in food technology improvements and innovations*. ed. M. Kuddus (Singapore: Springer Singapore), 63–78.

Singha, A. S., Priya, B., and Pathania, D. (2015). Cornstarch/poly(vinyl alcohol) biocomposite blend films: mechanical properties, thermal behavior, fire retardancy, and antibacterial activity. *Int. J. Polym. Anal. Charact.* 20, 357–366. doi: 10.1080/1023666X.2015.1018491

Song, H. G., Choi, I., Lee, J. S., Chang, Y., Yoon, C. S., and Han, J. (2022). Whey protein isolate coating material for high oxygen barrier properties: a scale-up study from laboratory to industrial scale and its application to food packaging. *Food Packag. Shelf Life* 31:100765. doi: 10.1016/j.fpsl.2021.100765

Sousa, F. M., Cavalcanti, F. B., Marinho, V. A. D., Morais, D. D. S., Almeida, T. G., and Carvalho, L. H. (2022). Effect of composition on permeability, mechanical properties and biodegradation of PBAT/PCL blends films. *Polym. Bull.* 79, 5327–5338. doi: 10.1007/s00289-021-03745-3

Sun, X., Li, Q., Wu, H., Zhou, Z., Feng, S., Deng, P., et al. (2023). Sustainable starch/lignin nanoparticle composites biofilms for food packaging applications. *Polymers (Basel)* 15:1959. doi: 10.3390/polym15081959

Taghinia, P., Abdolshahi, A., Sedaghati, S., and Shokrollahi, B. (2021). Smart edible films based on mucilage of lallemantia iberica seed incorporated with curcumin for freshness monitoring. *Food Sci. Nutr.* 9, 1222–1231. doi: 10.1002/fsn3.2114

Taherimehr, M., YousefniaPasha, H., Tabatabaeekoloor, R., and Pesaranhajiabbas, E. (2021). Trends and challenges of biopolymer-based nanocomposites in food packaging. *Compr. Rev. Food Sci. Food Saf.* 20, 5321–5344. doi: 10.1111/1541-4337.12832

Tsochatzis, E. D., Lopes, J. A., and Corredig, M. (2022). Chemical testing of mechanically recycled polyethylene terephthalate for food packaging in the European Union. *Resour. Conserv. Recycl.* 179:106096. doi: 10.1016/j.resconrec.2021.106096

Velázquez-Contreras, F., García-Caldera, N., de la Rosa, J. D. P., Martínez-Romero, D., Núñez-Delicado, E., and Gabaldón, J. A. (2021). Effect of pla active packaging containing monoterpene-cyclodextrin complexes on berries preservation. *Polymers (Basel)* 13:1399. doi: 10.3390/polym13091399

Visco, A., Scolaro, C., Facchin, M., Brahimi, S., Belhamdi, H., Gatto, V., et al. (2022). Agri-food wastes for bioplastics: European prospective on possible applications in their second life for a circular economy. *Polymers (Basel)* 14:2752. doi: 10.3390/polym14132752

Walker, T. R., McGuinty, E., Charlebois, S., and Music, J. (2021). Single-use plastic packaging in the Canadian food industry: consumer behavior and perceptions. *Humanit. Soc. Sci. Commun.* 8, 1–11. doi: 10.1057/s41599-021-00747-4

Wawrzynek, E., Baumbauer, C., and Arias, A. C. (2021). Characterization and comparison of biodegradable printed capacitive humidity sensors. *Sensors* 21:6557. doi: 10.3390/s21196557

Wypij, M., Trzcińska-Wencel, J., Golińska, P., Avila-Quezada, G. D., Ingle, A. P., and Rai, M. (2023). The strategic applications of natural polymer nanocomposites in food packaging and agriculture: chances, challenges, and consumers' perception. *Front. Chem.* 10:1106230. doi: 10.3389/fchem.2022.1106230

Xiao, Y., Liu, Y., Kang, S., and Xu, H. (2021). Insight into the formation mechanism of soy protein isolate films improved by cellulose nanocrystals. *Food Chem.* 359:129971. doi: 10.1016/j.foodchem.2021.129971

Xie, Q., Liu, G., Zhang, Y., Yu, J., Wang, Y., and Ma, X. (2022). Active edible films with plant extracts: a updated review of their types, preparations, reinforcing properties, and applications in muscle foods packaging and preservation. *Crit. Rev. Food Sci. Nutr.*, 1–23. doi: 10.1080/10408398.2022.2092058 [In press].

Xu, J., Yang, Z., Wang, Z., Li, J., and Zhang, X. (2023). Flexible sensing enabled packaging performance optimization system (FS-PPOS) for lamb loss reduction control in E-commerce supply chain. *Food Control* 145:109394. doi: 10.1016/J.FOODCONT.2022.109394

Yadav, A., Kumar, N., Upadhyay, A. P., and Anurag, R. K. (2021). Edible packaging from fruit processing waste: a comprehensive review. *Food Rev. Intl.* 39, 2075–2106. doi: 10.1080/87559129.2021.1940198

Yao, X., Hu, H., Qin, Y., and Liu, J. (2020). Development of antioxidant, antimicrobial and ammonia-sensitive films based on quaternary ammonium chitosan, polyvinyl alcohol and betalains-rich cactus pears (*Opuntia ficus-indica*) extract. *Food Hydrocoll.* 106:105896. doi: 10.1016/J.FOODHYD.2020.105896

Yousefi, H., Su, H. M., Imani, S. M., Alkhaldi, K., Filipe, C. D., and Didar, T. F. (2019). Intelligent food packaging: a review of smart sensing technologies for monitoring food quality. *ACS Sens.* 4, 808–821. doi: 10.1021/acssensors.9b00440

Zhang, Y., Du, Z., Xia, X., Guo, Q., Wu, H., and Yu, W. (2016). Evaluation of the migration of UV-ink photoinitiators from polyethylene food packaging by supercritical fluid chromatography combined with photodiode array detector and tandem mass spectrometry. *Polym. Test.* 53, 276–282. doi: 10.1016/j.polymertesting.2016.06.008

Zhang, W., Gao, P., Jiang, Q., and Xia, W. (2023). Green fabrication of lignin nanoparticles/chitosan films for refrigerated fish preservation application. *Food Hydrocoll.* 139:108548. doi: 10.1016/j.foodhyd.2023.108548

Zhang, Y., Luo, Q., Ding, K., Liu, S. G., and Shi, X. (2021). A smartphone-integrated colorimetric sensor of total volatile basic nitrogen (TVB-N) based on Au@MnO 2 core-shell nanocomposites incorporated into hydrogel and its application in fish spoilage monitoring. *Sens. Actuators B: Chem.* 335:129708. doi: 10.1016/j.snb.2021.129708

Zhang, M., Yang, B., Yuan, Z., Sheng, Q., Jin, C., Qi, J., et al. (2023). Preparation and performance testing of corn starch/pullulan/gallic acid multicomponent composite films for active food packaging. *Food Chem X* 19:100782. doi: 10.1016/j.fochx.2023.100782

Zhao, X., Cornish, K., and Vodovotz, Y. (2020). Narrowing the gap for bioplastic use in food packaging: An update. *Environ. Sci. Technol.* 54, 4712–4732. doi: 10.1021/acs.est.9b03755

Zhu, D., Guo, R., Li, W., Song, J., and Cheng, F. (2019). Improved postharvest preservation effects of Pholiota nameko mushroom by sodium alginate–based edible composite coating. *Food Bioprocess Technol.* 12, 587–598. doi: 10.1007/s11947-019-2235-5

Glossary

4.0 IR	Fourth Industrial Revolution
CO_2	carbon dioxide
BOPP	biaxially oriented polypropylene
EAB	elongation at break
EPR	extended producer responsibility
EU	European Union
EVOH	ethylene vinyl alcohol
FCM	Food Contact Materials
FDA	Food and Drug Administration
GRAS	Generally Recognized As Safe
HDPE	high-density polyethylene
LDPE	low-density polyethylene
LLDPE	Linear low-density polyethylene
N_2	nitrogen
NIAS	Non-Intentionally Added Substances
O_2	oxygen
OP	oxygen permeability
OTR	oxygen transmission rate
MAP	modified atmosphere
PBAT	poly (butylene adipate-co-terephthalate)
PBS	polybutylene succinate
PCL	poly-Ɛ-caprolactone
PE	polyethylene
PET	polyethylene terephthalate
PHAs	polyhydroxyalkanoates
PHB	polyhydroxybutyrate
PI	photoinitiators
PLA	polylactic acid
PP	polypropylene
PS	polystyrene
PVA	polyvinyl alcohol
PVC	polyvinyl chloride
PVDC	polyvinylidene chloride
rPET	recycle Polyethylene Terephthalate
TPS	thermoplastic starch
TS	tensile strength
VLDPE	very-low-density polyethylene
WVP	water vapor permeability
WVTR	water vapor transmission rate