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Bioactive Packaging as a Sustainable Solution For Food Preservation: A Review

Empaques Bioactivos Como Una Solución Sostenible Para La Conservación De Alimentos: Una Revisión

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Resumen

Los empaques convencionales son líderes en la industria alimentaria, pero presentan desventajas como su escasa biodegradabilidad y el aumento de la contaminación y las emisiones de gases de efecto invernadero. Los empaques bioactivos son una tecnología en tendencia que está ganando popularidad gracias a la incorporación de compuestos antimicrobianos y antioxidantes naturales procedentes de residuos agroindustriales y plantas infravaloradas. El desarrollo de envases bioactivos ofrece varias ventajas, como la prolongación de la vida útil, la reducción del deterioro de los alimentos, la mejora de la seguridad alimentaria y el uso de fuentes sostenibles. Este artículo de revisión explora el área en expansión de los empaques bioactivos. Describe cómo se incorporan los compuestos bioactivos a matrices de envasado hechas de polímeros naturales biodegradables como la celulosa, el quitosano, el ácido poliláctico, los lípidos y las proteínas. Además, se repasan las principales sustancias antimicrobianas y antioxidantes naturales extraídos de plantas como aceites esenciales y polifenoles en materiales de envasado de alimentos. Por último, se describieron las principales técnicas, como la encapsulación y la nanoemulsión, para incorporar estos compuestos bioactivos.

Palabras clave: Aceites esenciales, Antioxidantes, Empaques bioactivos, Polifenoles, Polisacáridos, Vida útil.

Abstract

Conventional packaging is a leader in the food industry but presents disadvantages such as poor biodegradability and increased pollution and greenhouse gas emissions. Bioactive packaging is a rising technology that is gaining popularity due to incorporating naturally occurring antimicrobial and antioxidant compounds sourced from agro-industrial waste and undervalued plants. The development of bioactive packaging offers several advantages such as extended shelf life, reduced food spoilage, improved food security, and use of sustainable sources. This review article explores the expanding area of bioactive packaging. Describe how bioactive compounds are incorporated into packaging matrices made of natural biodegradable polymers such as cellulose, chitosan, polylactic acid, lipids, and proteins. Additionally, review the main antimicrobial substances and natural antioxidants extracted from plants like essential oils and polyphenols into food packaging materials. Finally, the main techniques such as encapsulation and nanoemulsion were described to incorporate these bioactive compounds.

Keywords: Antioxidants, Bioactive packaging, Essential Oils, Polyphenols, Polysaccharides, Shelf life.

INTRODUCTION

Conventional packaging refers to systems primarily employing non-renewable materials, valued for their convenience, affordability, and superior moisture barrier, mechanical, and handling properties (Donkor et al., 2023). However, conventional packaging, which functions as a static, physical barrier, provides passive protection against microorganisms, oxygen, odors, and light (Fuciños et al., 2016).

The production and disposal of plastics derived from fossil fuels contributes to various environmental issues, including greenhouse gas emissions, environmental persistence, and pollution (Atiwesh et al., 2021). To address these challenges, recent advancements in packaging technology have transformed it into an interactive system. While plastics (42%), paperboard (31%), metals (15%), glass (7%), and other materials (5%) are commonly used as a packaging material (Jeevahan & Chandrasekaran, 2019), plastic remains as the dominant material in food packaging. Despite its desirable barrier properties, the non-biodegradable nature of plastic, coupled with low recycling rates, contributes to environmental pollution (Nogueira et al., 2020).

To mitigate these environmental concerns and enhance food quality, researchers have focused on developing active and biodegradable packaging solutions (Bhargava et al., 2020). Microbial spoilage remains a significant challenge in the food industry. To combat this, functional packaging with antimicrobial and/or antioxidant properties is being explored (Sofi et al., 2018). The development of bioactive packaging is one of the options currently being studied to delay food spoilage. There are different external and internal factors that cause food spoilage as shown in Figure 1. Bioactive packaging, which incorporates integrated components like antimicrobials, antioxidants, and phytochemicals, offers a promising approach to extend shelf life and improve food quality by actively modifying the food's environment through controlled release or absorption of bioactive substances (Pérez-Santaescolástica et al., 2022). Naturally occurring bioactive compounds from plant extracts have proven to be an effective alternative because they also often possess antimicrobial and antifungal properties (Jafarzadeh et al., 2020).

Food packages are necessary to protect food from environmental conditions such as humidity, oxidation, temperature, and deterioration by microorganisms, and facilitates the transport of food since it acts as a barrier that withstands mechanical damage (Versino et al., 2023).

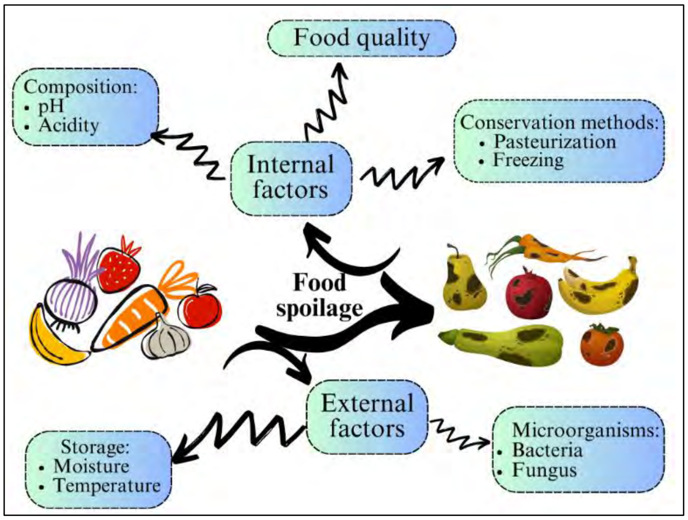

Figure 1. Internal and external factors that can affect the shelf life of food products.

BIOACTIVE PACKAGING

Bioactive packaging is an emerging technology that incorporates naturally occurring antimicrobial and antioxidant compounds into the food packaging matrix to preserve the quality of food products (Baghi et al., 2022). This innovative approach to packaging involves the development of materials that interact with the contents they hold to offer added benefits, such as improved quality, safety, and extended shelf life of the product. These materials often incorporate bioactive compounds, which are substances capable of exerting biological effects (Chandrasekar et al., 2023). Figure 2 shows an advantage and disadvantage comparison between conventional and bioactive packaging.

Figure 2. Main advantages and disadvantages between conventional and bioactive packaging

Films and Coatings

Films and coating technologies are employed for several crucial functions. Primarily, they act as barriers, offering protection against mechanical, chemical, and biological threats to food integrity. Notably, these technologies also minimize the migration of aroma, flavor compounds, and valuable products such as antimicrobials and antioxidants (Gupta et al., 2022). Edible films and coatings are synonymous terms describing edible packaging materials. But they differ in their mode of application: films are solidified prior to application, whereas coatings are applied in liquid form and subsequently dried. (Mohamed et al., 2020). Antioxidant, antimicrobial, antifungal, and even flavoring compounds can be added to these films and coatings to improve the quality and extend the shelf life of the food (Arroyo et al., 2019). On another hand, Betancur-D'Ambrosio et al., (2024) developed edible films using cassava starch, beeswax, and ethanolic propolis extract. Characterization of the edible films revealed that they exhibited antimicrobial activity against Aspergillus niger, reducing its growth by 51%. This makes these films suitable for use as coatings for fruits and vegetables. Aparicio-Fernández et al., (2018) developed edible films composed of carboxymethyl cellulose, prickly pear peel powder, and aqueous extracts from red prickly pear. To characterize these films, the researchers employed various techniques, including DPPH radical scavenging activity, total phenolic content determination, moisture content analysis, tensile strength testing, and puncture resistance measurement. The study demonstrated that the incorporation of prickly pear components significantly enhanced the antioxidant.

MATERIALS USED AS A MATRIX FOR EDIBLE FILMS AND COATING

Biopolymers derived from plants, animals, and microbial synthesis can be utilized to create eco-friendly food packaging materials with potential applications as carriers for functional compounds (Abdullah et al., 2022). These biopolymers can be polysaccharides, are abundant, affordable, and easy to process, but their hydrophilicity limits their water vapor barrier. Conversely, lipids offer better water vapor barrier due to their hydrophobicity. However, the lack of stretch in these materials relegates them mainly to coating applications (Chen et al., 2019). Other compounds can be integrated as antimicrobial agents to effectively inhibit microbial growth in packaging systems. This not only improves food quality but also contributes to environmental sustainability by reducing the dependence on fossil fuel-based plastics (Hu et al., 2022).

Biobased polymers

Biopolymers can be obtained from living organisms such as plants and microorganisms (Asgher et al., 2020). Proteins like ovalbumin, and beta-lactoglobulin can also be used as film-forming materials to thermal stability and interfacial wettability. On the other hand, carbohydrates like chitosan, and starch aldehyde along with other molecules, are used for enhanced antioxidant and antibacterial activity (Sahraeian et al., 2024).

Cellulose

Cellulose can be used as a filler or reinforcement agent in biodegradable/compostable polymers processing, including food packaging applications like formulation of biofilms, coatings, gels, or even hard packages (Alhanish & Ghalia, 2022). Ramesh & Radhakrishnan, (2019) created a biodegradable and environmentally friendly food packaging film by combining polyvinyl alcohol (PVA) with cellulose nanoparticles (CNP) extracted from potato peels and fennel seed oil. Analyses confirmed that the CNP-PVA film showed significant improvements in the mechanical properties. Moreover, it displayed enhanced antibacterial properties, antioxidant activity, and a reduced rate of oxygen transfer, indicating better food preservation potential. Das et al., (2022) developed an edible coating based on carboxymethyl cellulose nanoemulsion incorporated with cardamom essential oil. When applied to tomatoes, this coating effectively inhibited the growth of Escherichia coli and Listeria monocytogenes, extending the fruit's shelf life by mitigating weight loss, firmness decline, and microbial spoilage. Notably, the application of the edible coating did not adversely affect the organoleptic properties of the tomatoes, such as weight loss, firmness, and color. Liu et al., (2021a) created hydroxyethyl cellulose with sodium alginate based edible coatings incorporating asparagus waste extracts to enhance strawberry quality and shelf life. These coatings demonstrated significant antifungal activity against Penicillium italicum, delayed color change, reduced weight loss, and preserved polyphenolic and flavonoid content of the fruit. This study confirmed the effectiveness of these coatings in maintaining postharvest quality and extending shelf life of strawberries.

Microcrystalline cellulose is a partially degraded form of natural cellulose, or a synthetic fiber composed of crystalline regions organized into rod-like structures. These crystalline regions coexist with amorphous regions, preserving certain properties of native cellulose. Microcrystalline cellulose-based active films, leveraging these properties, offer innovative solutions for extending the shelf life of food products by providing antimicrobial protection against microbes and preventing lipid oxidation (Bangar et al., 2023). Cheng et al. (2021) developed active antibacterial films by combining microcrystalline cellulose and yam starch. Low concentrations of microcrystalline cellulose (5-25%) improved film properties, including reduced weight loss and increased thermal stability. Additionally, the incorporation of essential oils such as α-terpineol, eugenol, and carvacrol significantly enhanced the antimicrobial activity against S. aureus and E. coli. These films proved effective in extending the shelf life of pork by inhibiting bacterial growth and delaying spoilage.

Kowalczyk et al. (2021) developed edible films using methylcellulose and corn starch incorporated with fireweed (Chamaenerion angustifolium L.) extract to investigate their physicochemical and antioxidant properties. The results demonstrated that methylcellulose-based films were mechanically stronger than corn starch-based films.

Chitosan

Chitosan, a versatile biopolymer derived from chitin, has gained prominence in the food industry due to its unique properties, including emulsifying, antimicrobial, antioxidant, and gelling abilities (Tamer & Çopur, 2010). Popescu et al., (2022) developed chitosan-based coatings using medium and high molecular weight chitosan, combined with ascorbic or acetic acid and essential oils from sea buckthorn or grape seed. These coatings effectively preserved the postharvest quality of organic strawberries and apple slices during cold storage. The coatings reduced microbial load particularly yeast and molds, maintained higher levels of antioxidants and polyphenols, and lowered water activity, thereby inhibiting spoilage. These findings highlight the potential of chitosan-based coatings as a promising strategy for extending the shelf life and improving the quality of fresh fruits.

Chitosan-based edible coatings and films have demonstrated significant potential for preserving the quality and extending the shelf life of various food products, including fruits, vegetables, and even complex foods like meat. For instance, Sutharsan et al. (2023) developed chitosan-based bioactive films incorporated with catechin, quercetin, and luteolin. These composite films exhibited enhanced antioxidant and antimicrobial properties, effectively inhibiting the growth of foodborne pathogens (Listeria monocytogenes, Salmonella typhimurium, Escherichia coli and Staphylococcus aureus). When applied to beef, these films maintained the product's quality during storage at 4°C for two weeks and extended its shelf life by preserving color and inhibiting microbial growth. These findings highlight the versatility of chitosan-based films as a sustainable and effective approach for improving food safety and quality.

Polylactic acid (PLA)

Polylactic acid (PLA) is one of the major biodegradable polymers that can be obtained from microbial lactic fermentation processes. There is a growing trend in the use of PLA to formulate rigid and flexible food packaging because it exhibits excellent physical characteristics, is biodegradable, and is industrially available as a raw material (Kaushalya et al., 2019). In addition, the incorporation of bioactive molecules in PLA composite films has been reported, PLA can be processed into films using techniques such as compression molding, and solvent casting, and the most common is extrusion (Rojas et al., 2021). Mohamad et al., (2020) formulated bioactive PLA films incorporating curry essential oils, thymol, and kesum extracts as bioactive agents. The objective was to evaluate their potential to extend the shelf life of foods. The study found favorable compatibility between thymol, kesum extracts, and PLA matrix, while curry showed limited interaction. FTIR analysis confirmed the successful integration of the active agents into the PLA film. Direct food contact analysis revealed that all PLA films with bioactive agents effectively preserved chicken meat for up to two weeks.

Lipids-base materials

Materials such as waxes, paraffin, and shellac resins are used in creating protective films and coatings for food applications. These substances exhibit a characteristic that inhibits moisture penetration owing to their hydrophobic nature (Yousuf et al., 2022). Aguirre-Joya et al., (2018) developed a bioactive coating with optimal water vapor permeability value (WVP) formulated with candelilla wax and Aloe vera mucilage to which crude extracts of Larrea tridentata were added, the edible coating showed antioxidant and fungistatic capabilities. The study revealed potent antioxidant activity in Larrea tridentata leaf extracts, verified by *In Vitro* assays (ABTS, DPPH, FRAP, LOI). In addition, key phenolic compounds identified in Larrea tridentata leaves extracts (NDGA, Quercetin, and Kaempferol) via HPLC-MS were associated with a significant antifungal effect against common fruit-damaging fungi (*Botrytis cinerea, Colletotrichum gloeosporioides, Fusarium oxysporum* and *Alternaria alternata*).

Protein-base materials

Proteins used in packaging formulation require a denaturation step of the molecule to break the peptide bonds; the amino acids and peptides obtained can interact with other molecules through ionic, covalent or hydrogen bonds to strengthen the formula. (Soro et al., 2021). Pedro et al., (2023) optimized the formulation of whey protein concentrate films to enhance their overall mechanical properties. This involved incorporating essential oil derived from Foeniculum vulgare Mill. (fennel) into the films. The authors concluded that these materials hold promise for extending the shelf life of food products and potentially preventing foodborne illnesses caused by pathogenic microorganisms. In another study, eco-friendly packaging material based on black chickpea protein isolate, electrospun nanofibers, and citral-loaded nanoliposomes were designed. The authors concluded that the black chickpea protein isolate was successfully extracted and enhanced mechanical and thermal properties (Amjadi et al., 2024). On the other hand, protein mixture with bioactive compounds, and tea saponins extracted from Camellia oleifera residues were evaluated to prepare biodegradable films. The authors mentioned that the interaction of protein with chitosan, the obtained biopolymer films improved mechanical and physical properties (Nie et al., 2024).

Robledo et al. (2018) developed porous, heterogeneous quinoa protein-chitosan edible films incorporating 10% thymol nanoemulsions. These films were shown to inhibit fungal growth on inoculated cherry tomatoes within 7 days at 5°C. Yousuf & Srivastava (2019) investigated the efficacy of soy protein isolate-based coatings combined with honey for fresh-cut pineapple packaging. This combined treatment extended the shelf life of the fruit to 16 days at 4°C while significantly preserving phenolic compounds and inhibiting microbial growth. On another hand, Aitboulahsen et al. (2018) investigated a gelatin-based edible coating enriched with Mentha pulegium essential oil to extend the shelf life of strawberries. By incorporating two concentrations of Mentha pulegium essential oil (0.5% and 1%) into the gelatin coating, researchers found a significant reduction in microbial growth (count of total aerobic mesophilic flora, yeast, and molds) compared to uncoated strawberries.

POTENTIAL BIOACTIVE COMPOUNDS FOR FOOD PACKAGING

Essential oils

Bioactive agents, such as essential oils (EOs), have been incorporated into food packaging materials to enhance the shelf life and quality of the food. EOs are natural additives extracted from aromatic compounds and are known for their antimicrobial and antioxidant properties. By incorporating EOs into edible/biodegradable films and coatings, the packaging can help protect against oxidative and bacterial deterioration effects, thereby extending the shelf life of processed food (Akram et al., 2019). These secondary metabolites, abundant in aromatic and medicinal plants, play a crucial role in plant defense against pathogens. Monoterpenoids exhibit potent antibacterial activity by disrupting microbial growth and interfering with essential cellular processes (Siddiqui et al., 2024). While the precise mechanism of EOs against bacteria’s remains unclear, research suggests that their lipophilic constituents disrupt the bacterial cell membrane. This disruption compromises membrane integrity, leading to increased permeability and altered ion transport processes in bacteria (Samrot et al., 2021).

Polyphenols

Polyphenols are a group of chemical compounds of phenolic nature, found in a wide variety of plants. They are considered secondary metabolites, i.e., substances that are not essential for plant growth or development, but have other functions, such as defense against oxidative stress, pests, and pathogens (Williamson, 2017). Polyphenols like ellagic acid from pomegranate (Punica granatum) extracts have been implemented in bioplastics and edible coatings for the development of food packaging which proved to extend the shelf life of food due to compounds with antioxidant and antimicrobial activity present in pomegranate (Ko et al., 2021). Polyphenols exhibit antibacterial activity by interacting with various microbial cell sites, leading to the loss of cellular components, disruption of the cytoplasmic membrane, and subsequent cell death. The principal mechanism of action are the modification of the cell membrane permeability, the formation of cytoplasmic granules and the rupture of cytoplasmatic membrane; and other mechanism consists in disturbing intracellular functions by the formation of hydrogen bonding among phenolic compounds and enzymes (Zamuz et al., 2021; Rempe et al., 2017).

Phenolic acids

Phenolic acids are among the main bioactive compounds present in various plant species, confer color, flavors, and astringency to foods, Phenolic acids have been tested as crosslinkers to improve the physical and mechanical properties of some edible protein-based films, and it has also been reported that by incorporating phenolic acids into coating matrices or edible films, they have acquired antioxidant and antimicrobial properties. (Ordoñez et al., 2022). Kaczmarek, (2020) developed a study of the incorporation of tannic acid into edible films based on sodium alginate. The films were characterized using in vitro methods including DPPH assay, water vapor permeation rate (WVPR), and Fourier-transform infrared spectroscopy (FTIR-

IR). The results demonstrated improvements in the physical properties of the films and the acquisition of antioxidant properties by the edible films.

These compounds exert their antimicrobial effects through multiple mechanisms, including inhibition of nucleic acid synthesis, inactivation of essential bacterial enzymes, and disruption of cytoplasmic membrane integrity (Yang et al., 2023). The number and arrangement of functional groups attached to the benzene ring, as well as the length of the saturated side chain, significantly impact their ability to inhibit microbial growth (Lobiuc et al., 2023). Phenolic acids possess antioxidant properties through multiple mechanisms, including hydrogen atom transfer, single-electron transfer-proton transfer, sequential proton loss electron transfer, and transition metal chelation (Zeb, 2020). Some examples of bioactive compounds reportedly used in the formulation of bioactive packaging are listed in Table 1.

MAIN METHODS FOR THE EXTRACTION OF BIOACTIVE COMPOUNDS

Traditionally, hydro-distillation, maceration and shaking water bath are some methods used to extract compounds of interest present in some plants. These methods, also known as conventional extraction techniques, although easy to perform are known to be slow, inefficient, and require large volumes of solvent (Pogorzelska-Nowicka et al., 2024). In response, recent advances offer alternative methods such as microwave-assisted extraction and ultrasound-assisted extraction for a more efficient and sustainable approach to the extraction of bioactive compounds (Estrada-Gil et al., 2022). Microwave assisted extraction is an emerging technology that offers several advantages over conventional techniques. By subjecting plant materials to microwave irradiation, microwave extraction can significantly accelerate the extraction process, resulting in higher yields and shorter extraction times. Moreover, typically requires smaller volumes of solvents, primarily water and ethanol, which reduces costs and environmental impact (Bagade & Patil, 2021). Ultrasound assisted extraction, on the other hand, relies on the application of ultrasonic waves to disrupt plant cell walls and plasma membranes of plant cells and release the compounds of interest present in the cells such as polyphenols, essential oils, etc. The cavitation phenomenon generated by ultrasonic waves facilitates the mass transfer of solutes from the plant matrix to the extraction solvent (Dzah et al.,2020).

Additionally, bio-based techniques such as solid-state fermentation and submerged fermentation provide sustainable and eco-friendly approaches to producing valuable bioactive compounds. Solid and submerged fermentation has demonstrated considerable potential over time as a viable system for the industrial-scale production of numerous valuable products such as antioxidants, polyphenols, enzymes, antibiotics, and organic acids, among others (El-Sayed et al., 2020; Dey et al., 2016). No single method of extracting bioactive compounds can be taken as the best, the choice of extraction technique depends on various factors, including the target compounds, desired yield, and environmental considerations.

METHODS OF INCORPORATING PLANT-DERIVED BIOACTIVE COMPOUNDS

For the integration of bioactive compounds in edible films and coatings, it´s crucial to consider the type of packaging to be used and the materials to be used, the nature and characteristics of the bioactive compound to be used, and the type of food on which these films will be applied. Various methods exist for incorporating bioactive compounds or plant extracts into coatings, films, or packaging. However, the choice of method depends on factors such as compound type, packaging type, and desired packaging properties. (Nogueira et al., 2020). Some of the most reported methods for the addition of bioactive agents in bioactive packaging are described in Table 2.

Film formation by casting method

The casting method offers several advantages for film formation. It is a simple and cost-effective technique, requiring minimal specialized equipment. The wet-based process promotes improved particle interactions, resulting in homogeneous structures with fewer defects (Suhag et al., 2020). The simplicity and minimal equipment requirements of this method make it a popular choice for film production at laboratory and pilot scales (Lisitsyn et al., 2021).

The casting method suffers from several drawbacks, including the possibility of solvent retention, which can result in the incorporation of harmful chemicals within the polymer; and the potential for denaturing delicate biomolecules, such as proteins, due to the use of solvents (Anbukarasu et al., 2015).

Encapsulation

Encapsulation is one of the most widely used methods to preserve the properties of bioactive compounds, this technique is widely used in the elaboration of edible coatings and films as it helps to improve the bioavailability and stability of the bioactive compound. Encapsulation can be subdivided into two main categories: nanoencapsulation and microencapsulation. Nanoencapsulation specifically pertains to encapsulation particles ranging in size from 10 to 1000 nanometers, whereas microencapsulation encompasses particles with dimensions between 3 and 800 micrometers (Marcillo-Parra et al., 2021)

More specifically, microencapsulation protects the bioactive components within a homogeneous or heterogeneous matrix, resulting in the production of microcapsules endowed with numerous advantageous traits. This approach serves as a viable alternative for converting liquid, unstable substances into stable, free-flowing powders (Premi & Sharma, 2017).

The primary advantage of encapsulation technology in food packaging lies in its ability to enhance the performance and longevity of bioactive compounds. By encapsulating these compounds, they are shielded from degradation, volatilization, and undesirable interactions with packaging materials. This protection also improves compatibility between the bioactive compound and the packaging polymer, ensuring optimal performance (Becerril et al., 2020). Encapsulation technologies, while promising, face several disadvantages and limitations. Micro and nanoencapsulation processes often require specialized equipment and complex procedures, increasing costs. Additionally, the matrix material significantly influences the resulting micro and nanocapsules properties. Macro encapsulation, on the other hand, exhibits lower stability and fracture resistance (Huang et al., 2023).

Nanoemulsion technique

Emulsions are heterogeneous colloidal mixtures consisting of two immiscible liquids. This technique has generated interest in recent years to be applied in the elaboration of bioactive packaging in the food industry such as edible coatings, since through emulsification, edible coatings can be formulated with bioactive compounds that can protect and release sensitive bioactive compounds into the food (Katsouli et al., 2018).

Nanoemulsions differ from conventional emulsions because conventional emulsions are in most cases unstable and degrade over time. In addition, the particle size of nanoemulsions ranges from 10 to 100 nm, which makes them more stable, and they have a better release capacity from the encapsulated bioactive compounds. The main methods for the preparation of nano-emulsions consist of a one-step process in which all the components are combined in a suitable solution and homogenized to obtain nanodroplets. Alternatively, a two-step process can be used in which an aqueous solution of the components is first prepared and then combined with a separate solution of a biopolymer (Pandey et al., 2022).

The advantages of nanoemulsion include improving the targeting, adsorption, encapsulation, solubility, bioaccessibility, permeability, and bioavailability of weakly soluble ingredients due to the nanosized and large surface area of the droplets (Ahari et al., 2021). Nanoemulsion can also protect the loaded bioactive ingredients against hydrolytic and enzymatic degradation (Manzoor et al., 2023). The primary disadvantage of nanoemulsions is their extended emulsification time, which can lead to coalescence and a consequent increase in droplet size. The manufacturing process is associated with significant costs (Sneha & Kumar, 2022).

CHALLENGES AND PROSPECTS

Bioactive packaging represents a remarkable change in the field of food preservation; food packaging is no longer inherent in packaging that does not interact with the food. The use of sources of bioactive compounds derived from plants or agro-industrial wastes has been shown through various research studies to be viable and have the potential to be used in the formulation of bioactive packaging to extend the shelf life of food and even, why not, provide health benefits. However, although the development of bioactive packaging has great advantages, it still faces challenges because its use on an industrial scale is limited due to potential operating costs. Although bioactive compounds extracted from different plants and even agro-industrial wastes can impart potent biological activities to food packaging, it is important to consider and evaluate the possible negative effects that may occur, such as toxicity or alteration of the organoleptic characteristics of the packaged food, so it is important to evaluate the concentration and use the right amounts of extracts so that they do not pose a risk to the consumer and in turn ensure and maintain the quality of the product (Qian et al., 2021).

Edible coatings and films are the most studied forms of bioactive packaging at present because they are the easiest to implement, in addition to this, with the help of other techniques such as micro and nanoencapsulation are in trend because in most cases the bioactive compounds are very sensitive to temperature changes, so to be incorporated into a bioactive packaging matrix usually opt for encapsulated to be protected in a certain way within the polymeric matrix and in turn, the formed packages can be shaped by thermal methods such as thermo plasticization to confer more appropriate physical and mechanical properties (Majid et al., 2018).

CONCLUDING REMARKS

Bioactive packaging, integrating antimicrobial and antioxidant compounds from natural sources into biodegradable materials, offers a sustainable solution for food preservation. This emerging technology not only extends shelf life and prevents spoilage but also promotes the valorization of agro-industrial waste and undervalued plants. While challenges remain in process optimization and technological development, continued research, exploring diverse sources of active compounds and expanding applications, will pave the way for a more sustainable and functional future in food preservation. This interdisciplinary approach, combining materials science, food technology, and environmental studies, presents an opportunity for synergy between functionality and sustainability, making bioactive packaging an exceptional option for forward-thinking companies.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY

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

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Table 1. Bioactive compounds used in the formulation of bioactive packaging.

Bioactive compound	Function	Packaging matrix	Type of packaging	Assay	Reference
Cloves/prickly ash/ fennel geranium/ cinnamon extracts	Antioxidant and antibacterial properties	Chitosan base films	Film	DPPH/Total variable count of bacteria (*S. aureus* and *E. coli*)	Liu et al., (2021b)
Rosemary Extract	Antioxidant properties	Furcellaran/gelatin hydrolysate/glycerol	Film	DPPH/FRAP	Jancikova et al., (2019)
Monascus red/phycocyanin/safflower yellow	Antioxidant and other biological activities	Porcine skin gelatin/chitosan/	Film	ABTS method/Water sensibility and barrier properties/Physical properties	Liu et al., (2024c)
Satureja khuzestanica essential oil	Antimicrobial properties	PEG 6000/ Hydroxyl propyl methyl cellulose	Film	Physical and mechanical properties/ *Escherichia coli* ATCC 25,922, *Shigella flexneri* PTCC 1234, *Salmonella typhi* PTCC 1609, and *Staphylococcus aureus* ATCC 25,923	Aghajani et al., (2024)
Ellagic acid	Antioxidant and antimicrobial properties	Chitosan base film	Film	DPPH/ CFU bacteria count (*S. aureus* and *P. aeruginosa*)	Vilela et al., (2017)
Phenylalanine	Antimicrobial and antioxidant properties	Carboxymethyl cellulose/Polyvinyl alcohol	Film	Moisture adsorption capacity, water solubility, oxygen permeability, and water vapor transmission rate	Kurabetta et al., (2024)

Rosemary essential oil	Physical properties and antimicrobial properties	Starch-carboxymethylcellulose	Film	Water vapor permeability, Film thickness, solubility/ Agar diffusion method	Mohsenabadi et al., (2018)
Neem leaf extract	Antimicrobial and antifungal properties	Chitosan/Pectin	Film	Moisture, water solubility, water vapor permeability, optical properties, *Staphylococcus aureus* and *Aspergillus niger*	Firdaus et al., (2024)
Spearmint (*Mentha spicata*)	Antimicrobial	Chitosan/ carboxymethyl cellulose	Coating	Total variable count of bacteria (*Listeria monocytogenes*)	Shahbazi, (2018)
Grape seed extract	Antimicrobial	Chitosan	Coating	Plate count agar for total mesophilic and Psychotropic microorganisms.	Hassanzadeh et al., (2018)
Pomegranate peel extract	Antifungal	Alginate/chitosan	Coating	Mycelial growth of *Colletotrichum gloeosporioides* by agar diffusion technique	Nair et al., (2018)
Orange peel powder	Antimicrobial and antioxidant properties	Cellulose	Film	Mechanical and structural properties. Water barrier, DPPH, *Staphylococcus aureus* and *E. coli*	Riaz et al., (2024)
Gallic acid present in Rosemary extract	Antioxidant	Whey protein concentrate/carboxymethyl cellulose/glycerol	Coating	DPPH	Hosseini et al., (2020)
Mango puree/pineapple pomace	Antioxidant and antimicrobial properties	Corn starch/gelatin	Film	DPPH/FRAP/inhibition of growth with diffusion method on Petri dishes	Susmitha et al., (2021)
Green tea and rosemary polyphenolic extracts	Antioxidant	PLA	Film	DPPH/β-carotene bleach assay/Folin-Ciocalteu	Andrade et al., (2023)

Table 2. Methods used to integrate bioactive compounds into bioactive packaging.

Bioactive compound	**Incorporation method**	**Bioactive packaging matrix**	**Type of packaging**	**References**
Vitamin E	Nanoencapsulation	Carboxymethyl cellulose	Film	Mirzaei-Mohkam et al., (2020)
Pink pepper essential oil	Emulsion	Protein/pectin coating applied in polyethylene terephthalate boxes for storage of cherry tomatoes	Coatings applied to polyethylene terephthalate boxes	Locali-Pereira et al., (2021)
Mango leaf extracts	Supercritical solvent impregnation	Nano fibrillated cellulose	Film	Bastante et al., (2021)
Avocado by-products	Emulsion	Ethyl cellulose/Paper	Film	Acquavia et al., (2023)
Thymol and Carvacrol	Microencapsulation	Maltodextrin/soy protein	Coatings	Ulloa et al., (2017)
Thymol	Emulsion (nanoencapsulation)/casting method	Quinoa protein / Chitosan	Film	Robledo et al., (2018)
Date fruit (Khalas variety) seeds	Emulsion	Carboxymethyl cellulose-poly(vinyl)	Film	Lawal et al., (2024)
Oregano, tea tree and peppermint	Nanoencapsulation	Cellulose nanocrystals/chitosan	Film	Hossain et al., (2019)

Pistachio hull	Emulsion	Chitosan	Film	Kepekci et al., (2024)
Lavender oil	Microencapsulation	Gum acacia, sodium caseinate, gelatin, chitosan, β-cyclodextrin, and polyvinyl alcohol	Coatings	Zhang et al., (2020)
Undaria pinnatifida, *Sargassum pallidum*, *Ulva lactuca*	Ultrasonic homogenization	Cellulose nanocrystals	Film	Wang et al., (2024)
Mentha longifolia L. essential oils	Nanoencapsulation	Balangu seed gum	N.R	Rezaeinia et al., (2019)
Catechin	Nanoencapsulation	Chitosan-sodium tripolyphosphate	Coating	Shankar Kumar Mandal et al., (2019)
Carvacrol	Microencapsulation	Sodium Alginate	Film	Cheng et al., (2019)
Tea polyphenols nanoparticles	Emulsion	Pectin	Film	Yang et al., (2024)

*N.R: No Reported