Greening industry: case studies of successful sustainable polymer composites

Industria ecológica: estudios de casos de compuestos poliméricos sostenibles exitosos

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Abstract

Due to increased ecological knowledge about the need to reduce the environmental impact that conventional plastics have on the environment; over the last several decades, more sustainable packages have been developed. The goal of sustainable development is to replace conventional petroleum-based polymers with more environmentally friendly materials for be used in a variety of industrial productions. Valorization of agro-food wastes, biopolymers produced by yeast, algae, or bacterial fermentation, as well as those extracted directly from biomass, such as polysaccharides, proteins, and lipids, have derived in a great interest, especially for food packaging and agricultural films, but despite recent successful developments in bio-based polymers, this topic continue to require more research about potential application on foods. Edible polymers are mainly composed of polysaccharides, proteins and lipids, are nature-based materials, which can be easily consumed by human without any harmful effect on health. Since the attractive features of the edible polymers such as biodegradability and bio-environmental compatibility over non-biodegradable synthetic polymers, these polymers have found wide-spread applications in food industry.

This review mainly focus on the diversification of different sources of edible polymeric materials and applications as biofilms/coating technologies for foods preservation, active food packaging and functional food coating that are the main motivation for developing composites from polysaccharides, proteins and lipids, and these topics are discussed under the diverse application profile of novel edible composites coatings and films. Exploring new sources of edible polymers, incorporation of active components, nutrients and prebiotic and probiotic compounds allows to extend the shelf life, safety and functional properties of different food products.

Resumen

Debido al mayor conocimiento ecológico sobre la necesidad de reducir el impacto ambiental que los plásticos convencionales tienen en el medio ambiente; En las últimas décadas, se han desarrollado envases más sostenibles. El objetivo del desarrollo sostenible es reemplazar los polímeros convencionales a base de petróleo con materiales más respetuosos con el medio ambiente para su uso en una variedad de producciones industriales. La valorización de residuos agroalimentarios, biopolímeros producidos por levaduras, algas o fermentación bacteriana, así como los extraídos directamente de la biomasa, como polisacáridos, proteínas y lípidos, han generado un gran interés, especialmente para el envasado de alimentos y películas agrícolas, pero a pesar de los recientes desarrollos exitosos en polímeros de base biológica, este tema continúa requiriendo más investigación sobre su posible aplicación en alimentos. Los polímeros comestibles están compuestos principalmente de polisacáridos, proteínas y lípidos, son materiales de origen natural, que pueden ser fácilmente consumidos por el ser humano sin ningún efecto nocivo para la salud. Debido a las características atractivas de los polímeros comestibles, como la biodegradabilidad y la compatibilidad bioambiental con los polímeros sintéticos no biodegradables, estos polímeros han encontrado amplias aplicaciones en la industria alimentaria. Esta revisión se centra principalmente en la diversificación de diferentes fuentes de materiales poliméricos comestibles y aplicaciones como biopelículas/ tecnologías de recubrimiento para la conservación de alimentos, envasado activo de alimentos y recubrimiento funcional de alimentos que son la principal motivación para desarrollar compuestos a partir de polisacáridos, proteínas y lípidos, y estos temas se discuten bajo el perfil de aplicación diverso de nuevos recubrimientos y películas de compuestos comestibles. La exploración de

nuevas fuentes de polímeros comestibles, la incorporación de componentes activos, nutrientes y compuestos prebióticos y probióticos permite extender la vida útil, la seguridad y las propiedades funcionales de diferentes productos alimenticios.

Introduction

Modern food system would be incapable to advance without food packaging that are developed around synthetic or semi-synthetic materials like polyethylene, commonly known as plastic or single-use-plastic (Sundqvist-Andberg and Åkerman, 2021; Phelan et al., 2022). However, the use of plastic has shown an increase rejection in relation to human health and environmental impact (Wang et al., 2021). Most environmentalists are concerned about the increased plastic pollution generated by the food industry (Kan and Miller, 2022). Food industry has been criticized for use of non-biodegradable, non-eco-friendly, and toxic production methods, materials and treatment strategies (Khalid et al 2022). The main concern is plastic pollution in the food industry; they are non-biodegradable which leads to their accumulation in the ecosystem resulting in serious ecological and health issues (Gupta, 2022). The rising environmental concerns caused by the excess use of synthetic materials have diverted the world's attention towards sustainable materials along with a circular economy approach using recycling routes. As a result, the demand for sustainable and eco-friendly alternatives to plastics is growing. In this way, a better alternative to food grade plastics is the use of nature derived polymers having characteristics similar to conventional plastics. This fact gives an opportunity for edible and biodegradable biopolymers in food production and packaging (Mitelut, 2021). Sustainable polymers are materials derived from renewable, recycled and waste carbon resources and their combinations, which at the end of life can be recycled, biodegraded or composted (Mohanty et al., 2022).

Besides, consumers nowadays show an increasing demand for food products that have been less processed but also require a longer shelf life and to maintain nutritional and sensorial qualities during storage. On the other hand, the food industry is facing new challenges in terms of sustainability and health implications about packaging and processing techniques. These requirements represent real challenges when working with highly perishable food products attributed mainly to high water activity of products such as fruits and vegetables and meats (Mitelut et al., 2021)

In this context, in the last years, edible coatings and films have been intensively developed and studied since they present capacity to improve the foods quality, shelf life, safety, and functionality when different food products are treated with edible films and coatings (Alvarez et al., 2021; Nair et al., 2020; Kumar et al., 2022).

In food industries, the main reasons for considering the healthy to eat polymers came into effect with the introduction of new food product categories, such as healthy, convenient and environment friendly high-quality products. The edible polymers are produced solely from renewable and safe to eat components; hence are expected to degrade more easily than other polymeric materials (Mohanty et al., 2022).

Naturally occurring biodegradable polymers of agricultural or marine wastes, plants, or animals have been utilized to replace the conventional non-biodegradable plastic used to package food (Gutiérrez, 2018a; Mangaraj et al., 2019). Therefore, food packaging processes derived from hydrocolloids are widely used due to their excellent barrier and mass transfer properties, due to which spoilage of the product can be delayed by increasing its shelf life. Additionally, polypeptides have a higher strength and antimicrobic action (Zhang et al., 2020). These edible coatings enough the uptake of nutrients by making use of composite polymer films or bioactive films that may aid in the delivery of vitamins or drugs (Pereda et al., 2018).

Edible coatings can be applied through different techniques, like dipping, spraying, or coating, in order to control moisture transfer, gas exchange, or oxidative processes. Furthermore, some functional ingredients can be incorporated into an edible matrix and applied on the surface of foods, thus enhancing safety or even nutritional and sensory attributes (Kumar et al., 2022). In the case of coated fruits and vegetables, their evolution of quality parameters, such as color, firmness, microbial load, decay ratio, weight loss, sensorial attributes, and nutritional parameters during storage conditions, should be carefully monitored (Mitelut et al., 2021).

These polymers can be classified as agricultural, marine, and animal based on their origin. Such polymers have applicability as coating materials, films, and packaging materials or preservative and protective materials. The ability to form films and coatings of these polymers is used in food packaging and delivery of bioactive substances such as nutraceuticals and probiotic bacteria (Gupta et al., 2022).

Also, natural polymer-based nanocomposites have received significant attention in both scientific and industrial research in recent years. Such nanocomposites consist of natural biopolymers (e.g., chitosan, starch, cellulose, alginate and many more) derived from plants, microbes and animals that are abundantly available in nature, biodegradable and thus eco-friendly, and can be used for developing nanocomposites for agriculture and food industry applications (Azadi et al., 2024). Biopolymer-based nanofilms or hydrogels may be used as direct product coating to extend product shelf life of different foods (Wypij et al., 2023). In this way, food waste can be used extensively to make nanocomposite polymers, that are useful in a variety of industrial applications. Biodegradable components like lignin and chitin, which are sourced from animal products or crop leftovers, are used to create the cutting-edge polymers (Mishra et al., 2023). The mechanical properties and endurance of the polymers are improved by including these natural components, making them suitable for a variety of industrial fields. In the rapidly expanding sector of biocomposite polymer materials, there is a big emphasis on using food waste as a viable feedstock. Biocomposites made from food waste have better mechanical strength and barrier qualities than conventional materials. They are a desirable replacement for conventional synthetic polymers due to their sustainability, which also expands the variety of possible uses. Inorganic and organic nanoparticles are mixed with biopolymers to form nanocomposite materials based on biopolymers (Tripathi et al., 2024).

Polymers for formulation of edible coatings

Edible polymers referred to as polymeric materials that can be easily ingested with no adverse effects on the consumer. Therefore, natural polymers are of great interest for use in food packaging. Their advantages are that protect the food against loss of nutrients, control mass transport properties of the molecular composition of food from inside to outside and slow down the adverse changes to the product. Biological polymers can be obtained from different sources like plants, animals, microbial, among others (Kouhi, et al., 2020).

The food industry is striving towards creating novel forms of edible films/coatings. Using the films that can be consumed directly as an alternative to pack fresh and processed food items can allow to enhance the quality, safety, display, transportation, along with their storage; extending the shelf life and preserving the quality of the product. Edible films can serve as transporters for nutrient additives such as vitamins, antimicrobials, antioxidants, probiotic and prebiotic compounds resulting in a functional performance and improved qualities that stimulate the sensory perception (Wypij et al., 2023). Furthermore, edible films may be profitable to agricultural and food industry derivatives considering they are made from sustainable, environment friendly and comestible products such as proteins, lipids or carbohydrates. Although lipid-based films offer strong water barrier qualities, they are brittle. Protein and polysaccharide-based films, on the other hand, have strong mechanical characteristics and hence can tolerate handling (Gupta et al., 2022).

The waste generated from the agricultural activity in the form of biomass can be hydrocolloids that have the ability to form viscous solutions or gels when dissolved in aqueous environment (Pirsa and Hafezi, 2023). They are used as thickeners, stabilizers, emulsifiers, water retention, gel-forming agents, and dietary fibers (Goff and Guo, 2019). Some examples of commonly used hydrocolloids are polysaccharides and polypeptides. Polysaccharides are long polymeric chains of carbohydrates that are abundantly found in nature. In food industry, natural polysaccharides are the most extensively used biopolymers because they are renewable and have a high level of biocompatibility and biodegradability. Polysaccharides are preferred over other polymers because of their biocompatibility, bioactivity, homogeneity, and bioadhesive properties. Polysaccharide-based composites derived from natural sources have been widely exploited due to their multifunctional properties, particularly in nutrient delivery systems in food applications (Benalaya et al., 2024).

Plant cell walls contain cellulose, hemicelluloses, and lignin in addition to pectin. It belongs to the same group of polysaccharides as agar and mucopolysaccharides which form gels (Chandel et al., 2022). One of the most crucial hydrocolloids for industry is pectin, which is employed in many different food products. Citrus and apple pectin are the main industrial sources of high-methoxyl (>50%) pectin, whereas sunflower pectin is a naturally occurring source of low-methoxyl (50%) pectin (Basak and Annapure, 2022). Some of the common polysaccharides that are present in crop residues are cellulose and starch. Cellulose is the most abundantly present biomass and it is a crystalline bio-polymer obtained primarily from woody plants (Gutiérrez, 2018). Cellulosic derivatives such as hydroxypropyl cellulose (HPC), hydroxypropyl methylcellulose (HPMC), methylcellulose (MC), and carboxymethylcellulose (CMC), are employed in edible coatings and films. Cellulose and its derivatives when heated form a gel and undergo reversible thermo-gelation (Williams and Phillips, 2021). The cellulosic films are flexible, lipid resistant, water soluble, clear, tasteless and have an oxygen transfer barrier. Pure starch is an odorless white powder. This polysaccharide is composed of the molecules of amylose and amylopectin. Starch, which is present in fruits, seeds, and roots in the form of grains in leaves, tubers, stem core, and rhizomes, is the most significant polysaccharide for storing energy in plants (Zhang and Zhaj, 2020; Bojarczuk et al., 2022).

Moreover, a large amount of waste is generated from the sea-food industry in the form of shells, scales, etc. These waste products when negligently disposed of are harmful as they have a high biological oxygen demand, chemical oxygen demand, total suspended solids, microbial pathogens and organic matter. Due to the high abundance of biodegradable chitosan (a derivative of chitin) in the marine-food industry, they have been exploited in the food and agricultural sectors (Babu et al., 2019; Yadav et al., 2019). Chitin is a linear polysaccharide obtained from animal (crustaceans, and other invertebrates) that is extremely hydrophobic and includes acetyl and amino groups inside its unit. It is insoluble in water and conventional organic solvents, but it is soluble in specialized solvents (Hasan et al., 2022). Chitosan is a partly acetylated (1 → 4)-2-amino-2-deoxy-β-D-glucan obtained by deacetylating chitin. Being a non-toxic biodegradable polymer, it has good biocompatibility, and exhibits antibacterial activity against a variety of pathogens. Chitosan has good film-forming characteristics, enabling the production of films with low gaseous (O_2 and H_2O) transport and is majorly used to protect food products from microbial contamination water (Manigandan et al., 2018).

The seaweed alginate is a long-chain hydrophilic polymer that gives flexibility and strength to the cell walls of the algae. Alginate is a safe and natural food ingredient (Bi et al., 2022). Alginate has excellent biological properties compared to other seaweed polysaccharides, including ion cross-linking, pH sensitivity, biocompatibility, and biodegradability, which have been extensively used in the food and nutraceutical industries. Alginate is the only polysaccharide with carboxyl groups naturally present in each component residue (Tao et al., 2024).

Also, animal-based biopolymers derived from animals are of much interest due to their bio-degradable, compostable, sustainable and ability to reduce CO_2 levels in the atmosphere. This increases their demand for food wrapping as it provides enhanced protection from microbes and improves the quality and shelf-life of the products (Wankhade, 2020). Some important animal-based polymers used in the food sector are collagen and gelatin. A promising resource for protein can be found in collagen and gelatin derived from animal byproducts. Their special characteristics, as well as biodegradability, edibility, and bioavailability make them widely applicable in food industry (Ahmad et al., 2024). The hydrolyzed collagen produces another form of polymer called gelatin with a variable amino acid content, which alters its gelling and viscosity potential. It is utilized to encapsulate food ingredients with low moisture or in the oil phase. This type of encapsulation protects against oxygen and light while determining the dose of a particular compound. Furthermore, gelatin films and coatings have the property to extend the shelf life and prevent the deterioration of numerous food products such as fish, meat, and fruits and have a vital role in encapsulating probiotics (Rather, et al., 2022). In this way, Rather et al., (2022) reported that meat coated with gelatin films allow to inhibit O_2, H_2O, and lipid transfer. The application of gelatin and chitosan as alternative biomaterials for edible biodegradable polymers for food packaging is considered one of the best ways to reduce plastic pollution in the environment (Elgadir et al., 2022). Collagen and gelatin can be used for the development of functional foods and to improve the quality of processed foods (Ahmad et al., 2024).

Moreover, polymers can be employed more widely as matrices in blends and composites. A composite is a system made up of two or more different elements linked together to form a multiphase system with many components while the individual elements maintain their physical and chemical properties. Polymers can serve as a matrix or filler in composites. When monocomponent synthetic or natural materials cannot give the needed physical and/or physicochemical qualities, composite systems are adequate (Benalaya, 2024). Composites can be made from polymers, both synthetic and natural. Natural and synthetic polymers are blended to develop a new breed of materials with more diverse properties that may be used in a wider range of applications. The production of synthetic polymers, present advantages like as product consistency and ease of production, and also raised environmental concerns due to their nonbiodegradability and potential toxicity, which has led to an increase in the popularity of natural polymer-based composites (Benalaya, 2024). Either when two or more polymers are physically combined, while molten or while dissolving in a suitable solvent, blends are created (Albdiry, 2024).

The formulation of composite films by combining different biopolymers has been a commonly used model to customizing properties of film and thus developing edible films attending to the required functional characteristics and necessities for food packaging (Pereda et al., 2018). Green packaging films made of natural macromolecular polymers can be used for food packaging, but the performance of such packaging films could be not totally satisfactory. Alternatively, different agents such as crosslinkers are often used to compensate for the defects.

Improving Physical Properties of Edible Films and Coatings

Modification of sensory, nutritional and functional properties, including mechanical properties, of edible coatings, can be obtained by adding various compounds. The basic components or matrix components of edible coatings and films are hydrocolloids (polysaccharides) and the matrix of coatings can be modified with plasticizers (increasing their elasticity and extensibility), emulsifiers or surfactants (improving the stability of the emulsion) and crosslinking agents (improving physical properties) (Benalaya et al., 2024). Edible coatings can be used directly on different food products (such as fruits and vegetables, meat); and they can be carriers of other food additives such as anti-oxidants, nutraceuticals, flavourings, etc., which modify the functional properties of different food products.

- Plasticizers (glycerol, sorbitol, sucrose, mannitol, acetylated, monoglyceride, polyethylene glycol, and xylitol) added to coatings to increase flexibility and prevent coatings from blistering, flaking, and cracking.
- Emulsifiers (soy lecithin, stearic acid, and tweens) and surfactants (tweens) added to improve coating adhesion.
- Antimicrobial agents (nisin, natamycin, phenolic compounds, natural seed extracts, and essential oils) added to improve the antimicrobial activity of a coating.
- Antioxidants (ascorbic or citric acid) added to coating food matrices to prevent oxidative rancidity, degradation, and discoloration.
- Nano-compounds (like metal oxides as ZnO or TiO_2).

These functional compounds are seen now as a key component of edible films/coatings for prolonging the shelf life of food products such as fruits and vegetables and they were already tested on various fruits (guava, pear, and blueberries) and vegetables (cucumber, capsicum, and mushroom) focusing also on safety and nutritional aspects (Benalaya et al., 2024; Mitelut et al., 2021).

Application of Natural Polymers in Food Products

Proteins and polysaccharides are the main types of polymers with potential application in food preservation. Several polysaccharides, including starch, cellulose, chitosan, galactomannans, carrageenans, alginates, agars, inulins, pectins, xanthans, and gums, are abundant in nature and important sources of nutrients. Polysaccharides are utilized as food additives because of their functional properties as thickening, stabilizing, gelling, and emulsifying agents (Zhao et al., 2023). Proteins have the ability to produce and stabilize emulsions, foams, and gels, as well as enhance viscosity and water holding capacity. Some of the key components include gelatin, milk proteins, egg proteins, and plant proteins (Benalaya et al., 2024). The functional properties of film/coating forming solution can be improved combining polysaccharides (e.g., starch, alginate, cellulose and chitosan) with proteins (e.g., milk protein, soy protein, collagen and gelatin). These composite edible films allow improving their mechanical and physical properties. For example, laminated chitosan/pectin films are based on the interaction of cationic chitosan groups with anionic pectin groups. The films prepared with chitosan and gelatin are homogeneous due to the good miscibility between the two biopolymers, which leads to improved functional properties of blended films compared to those obtained from each polymer alone. This fact could be explained by the formation of electrostatic interactions between the ammonium groups of chitosan and the carboxylate groups of gelatins (Zhao et al., 2023).

Edible films can be used as carrier of nutritional compounds like vitamins and minerals, bioactives compounds, anti-browning and antioxidants agents and antibacterial compounds (Alvarez et al., 2018; Bambace et al., 2024). Antimicrobials enhance the durability of products and minimizes pathogenic decay on food surfaces, assuring the safety of food consumption (Gutiérrez, 2018). Addition of antimicrobial compounds to edible coatings and films that directly touch the surface of foodstuff, where pathogenic contamination is most prevalent, can be more effective and substitute the inclusion of preservatives. Lazaridou et al., (2020) reported that the active-coating alternatives proved to be more effective than the application by spray of antimicrobial agent since it allows for continual diffusion of active ingredients into the food, remaining at high concentrations for extended periods. Essential oils have taken a great attention in recent years as active compounds that can be added into film/coating forming solution due to their antimicrobial and volatile characteristic that allows using low quantities that are safe to consume (Alvarez et al., 2018). In this sense, Hashemi and Mousavi Khaneghah (2017) developed a gum film with the addition of oregano essential oil. A significant antibacterial activity was detected in films containing oregano essential oil against *Escherichia coli*, *Pseudomonas aeruginosa, Salmonella typhimurium, Staphylococcus aureus*, and *Bacillus cereus*.

Kumar et al., (2018) analyzed fresh-cut apple samples coated with edible coatings (carboxymethyl cellulose and aloe vera) and anti-browning agents in different combinations, with only one active ingredient or both. The samples coated with the edible coating material along with the anti-browning agents helped preserve the quality of the samples. It was observed that apple slices coated with carboxymethyl cellulose and aloe vera show a significantly lower microbial load. The coated apple samples showed an improved firmness compared to the untreated samples. Polyphenol oxidase and peroxidase enzyme activity was also lower in the coated samples (Kumar et al., 2018). Besides, Kumar et al., (2020) investigated the effect of a composite edible coating from chitosan-pullulan and pomegranate extract on the shelf life and quality parameters of green bell pepper samples. This novel formulation of edible coatings allows to maintain total soluble solids content, titratable acidity, pH, phenolic content, flavonoid content, antioxidant activity, firmness, and sensorial attributes over the entire storage period. A positive effect on the quality and shelf life of the samples was attributed to the edible coating.

Lara et al., (2020) studied the effect of xanthan gum-based edible coatings on fresh-cut lotus roots stored at a temperature of 5° C for 16 days. Citric acid was added as an anti-browning agent and glycerol as a plasticizer. It was observed that the treated samples had a significant reduction in the total color changes compared to control samples. In addition, the enzymatic browning of lotus root was decreased and a lower microbial count was recorded to the treated samples compared to non-coated fresh-cut lotus root samples, during all storage period. Basiak et al., (2019) studied the effects of two different starch-based edible coatings applied on coating plums, one containing only starch and the other one containing starch and whey protein. The results showed that when applying the coatings prepared with starch and starch-whey protein increased the total resistance in the water vapor pathway of individual plums by 60–75% at high transpiration potentials. Wani et al. (2021) performed a carrageenan edible coating with arabic and xanthan gums with addition of lemon grass essential oil. Edible coatings were analyzed to improve or maintain the postharvest quality of strawberries samples over a period of 12 days at refrigerated condition. The result showed that the coated strawberry samples had a reduction in weight loss, retained the ascorbic acid better, had better antioxidant activity, and had improved firmness.

Alvarez et al., (2022a) studied a novel antifungal edible coating based on citrus pectin and beeswax and enriched with eugenol, geraniol, propolis extract as alternatives to reduce sour rot and preserve the postharvest quality of 'Valencia' oranges. These natural agents were incorporated into the edible coatings formulation and then applied to inoculated oranges. Edible coatings enriched with bioactive compounds reduced disease incidence and severity by 75 to 100% compared to uncoated oranges after 20 days of storage at 20°C. Furthermore, all tested edible coatings maintained the oranges sensory and physicochemical quality. Overall, the eugenol-enriched pectin presents the best antifungal activity, showing potential as a safe, bio-based alternative to conventional waxes containing synthetic fungicides for the management of citrus postharvest sour rot. In addition, Alvarez et al., (2022b) performed pectin-beeswax edible coatings containing essential oils and plant extracts as antifungal ingredients to reduce postharvest losses in 'Valencia' oranges. After 4 weeks of cold storage, geraniol and eugenol-based coatings reduced disease incidence by more than 50%, while eugenol coating was the most effective to reduce fungal severity. This coating was selected as the best essential oil by its potential to reduce citrus postharvest losses. In the same way, Alvarez et al., (2023) developed a novel pectin-based antifungal edible coatings by the addition of natural extracts or essential oils, and their ability to control green mold, caused by *Penicillium digitatum*, and preserve postharvest quality of oranges. Edible coatings containing geraniol and eugenol reduced disease incidence by up to 58% after 8 days of storage at 20°C. Moreover, these edible coatings were the most effective on artificially inoculated cold-stored oranges, with green mold incidence reductions of 50% after 4 weeks at 5°C. These authors concluded that the coating with eugenol addition was the most promising and could be a good natural, safe, and eco-friendly commercial treatment for preserving orange postharvest quality.

Muley et al., (2020) studied the effects of a novel functional coating made from whey protein isolate, chitosan, and glycerol on the shelf-life extension of strawberries stored for 8 days under refrigerate conditions. The results showed that the coated samples had a reduction in weight loss, pH, color modifications, titratable acidity, total phenolics, and DPPH and a shelf- life extension for 3 days respect to untreated samples. Vilaplana et al., (2020) studied the antifungal effect of an edible coating based on chitosan applied on blackberry samples. Chitosan forming solutions was prepared with acetic or lactic acid and then was applied on the blackberry samples in order to evaluate the antifungal activity. The results showed that the samples coated with chitosan and lactic acid present the best antifungal effect. Arnon-Rips et al., (2021) studied the addition of two functional compounds (vanillin and trans-cinnamaldehyde) into chitosan forming solution that was applied on fresh-cut melon slices. The results showed that the tested films produced well-adhered coatings that allow to maintain the fresh-cut melon quality attributes and to improve the shelf life without altering the sensorial attributes. Furthermore, a significant antibacterial effect (6-log CFU/mL microbial count reduction) was observed when mandarin juice was added to the chitosan and vanillin and trans-cinnamaldehyde mixture.

Alejandra Moreno et al., (2020) studied the shelf life of raspberries treated with an edible coating based on gelatin with ethanolic-based extract of propolis. The addition of propolis changes the mechanical properties of the edible films, but also more colored films with lower transparency. This edible coating was applied to the raspberries samples and the fungal decay was assessed at cold storage at 5° C. The authors report a notable antifungal activity in treated samples; also, the coating with propolis added enhanced the shelf life of raspberries during cold storage.

On the other hand, Passafiume et al., (2020) studied the effect of three edible coatings based on aloe vera gel, hydroxypropyl methylcellulose, and lemon essential oil-based composite coating on prolonging the shelf life and quality of fresh-cut kiwifruits. The results showed that the coated samples presented reduced weight loss and browning and maintained higher firmness, brightness, greenness, and soluble solid contents. The incorporation of aloe vera gel and aloe vera gel + lemon essential oil into edible coating reduced the microbial load compared to the control samples. Ke et al., (2023) reported that direct addition of vanillin improved the physicochemical properties and antibacterial activities of gelatin and sodium carboxymethyl cellulose composite films. Also, the two films had good soil degradability and antibacterial property on *Escherichia coli* and *Staphylococcus aureus*. Liu et al., (2021) tested the effects of mixed edible coating performed with hydroxyethyl cellulose and sodium alginate with asparagus waste extract on the postharvest quality of strawberries. This edible coating allows to maintain the total flavonoid and phenolic contents as well as significantly delayed color change and weight loss. In addition, this novel edible coating presented an antimicrobial effect against *Penicillium italicum*.

Guerreiro et al., (2021), performed a study aimed to test different sodium alginate-based edible coatings, enriched with essential oils (eugenol and citral) as antimicrobial compounds, for maintaining postharvest quality and prolonging storage life of strawberry fruit. Quality parameters of the coated fruits with essential oils were better than samples treated without essential oil, showing good preservation quality. In other study, Guerreiro et al., (2023) studied the effects of edible alginate coatings in prolonging the shelf life of kiwifruit. During cold storage, as consequence to coating applied, it was observed that the color and soluble solid content parameters increased, firmness decreased over time and weight loss was the parameter with higher significant differences. In addition, Duong et al., (2022) developed an alginate-based edible coating with the addition of various concentrations of $CaCl_2$ solutions in order to maintain the shelf life of rose apple fruits during cold storage. The results demonstrated that the $CaCl_2$ addition decreased water vapor permeability and oxygen permeability compared to the alginate films. The total phenolic content and antioxidant activity in treated fruits were significantly higher respect to the control sample, over 10 days of storage at refrigeration temperature.

Manrich et al. (2017) developed an edible film formulated with cutin extracted from the tomato peel along with pectin. These films were similar to the tomato peel when compared based on mechanical and thermal properties.

Oyom et al., (2022) studied an edible coating containing modified starch from sweet potatoes and cumin essential oil applied on pear samples. The coating enables to control the respiration rate and delay the weight loss and maintained fresh firmness after 21 days of storage. Zhang et al, (2022) studied the application of edible coating solutions prepared with starch to reduce losses and increase the shelf life of fresh strawberries. In obstacle technology, starch edible coating as active packaging or applications of edible coatings can be added to low-temperature storage and the use of modified atmospheres (Zhang et al., 2022). Taha et al., (2022) analyzed the advantages of apply a starch-silver nanoparticle coating on the physical, chemical, and microbiological qualities of strawberries during postharvest life. Yıldırım-Yalçın et al. (2022) applied an edible coating based on maize starch enriched with grape seed extract and studied its effects of the strawberry's quality properties during refrigerated storage for 12 days. The reported results indicate that the coating applications reduced the water loss, pH changes, and microbiological counts of strawberries significantly.

Hosseini et al. (2018) develop a bio-nano composite films using gelatin obtained from fish and chitosan nanoparticles. The addition of nanoparticles to fish gelatin film enhanced its vapor barrier and elastic modulus that resulted in even distribution of nanoparticles within the film scaffold at reduced loading rates (Hosseini et al., 2018). Leena et al., (2020) studied a delivery system using nano-structured edible coating based on zein enriched with resveratrol as a controlled release system of the bioactive compound. The obtained edible coating was applied on apple slices. These authors demonstrated that the treated apple slices retained better color, due to the antioxidant effect of resveratrol added as a functional ingredient. In addition, it was reported that the coating allowed to apple slices lost lower moisture content. Dehghani et al, (2022b) performed a bilayer antibacterial film prepared using polylactic acid and chitosan nanofiber. The reported that the bilayer films showed a significant antibacterial activity against *Escherichia coli* and *Staphylococcus aureus*. Besides, Dehghani et al (2022a) performed a fish gelatin conjugated with bitter almond gum (BAG) and demonstrate that a composite film may be suitable material for shelf-life extension of tomato.

In edible bioactive films and coatings, the release characteristic is not required as they would be eaten whole along with the food. Therefore, they can be supplemented with probiotics bacteria, prebiotics (supplements required for the growth of probiotic strains) that have beneficial effects on human health (Bambace et al., 2022). In this sense, the performance of edible coating as a new carrier for probiotic strains is a very interesting topic for researchers. Alvarez et al., (2021) performed a study aimed to evaluate the effect of probiotic supplementation of fresh-cut apple coated with alginate-prebiotic on its nutritional, safety, and sensory characteristics. A new non-dairy probiotic food was developed by adding prebiotics (oligofructose and inulin) and probiotic cultures (*Lactobacillus rhamnosus* and *Bifidobacterium animalis* subsp. *lactis*) to fresh-cut apple. Both probiotics successfully remained above 9.0 log CFU/g in the product after 8 days of storage. Microbiological and nutritional quality were maintained; however only those samples with prebiotics and *B. lactis* remained sensorially acceptable after 8 d. Furthermore, both probiotics exerted a significant bactericidal effect against *L. innocua* inoculated on apple cubes. Thereby, apple pieces coated with prebiotic-alginate solution constitute a promising alternative to design new carriers for probiotic bacteria.

Bambace et al., (2021) studied the potential use of fresh blueberries as carriers of *Lacticaseibacillus casei* and *Bifidobacterium animalis* subsp. *lactis* incorporated into alginate-based prebiotic coatings. A protective effect was reported since prebiotic enrichment allowed maintaining both *L. casei* and *B. lactis* viability above the minimum recommended levels (6 log CFU/g) up to the end of storage, ensuring their beneficial health action. Both probiotics exerted a biocontrol effect on inoculated *L. innocua* with reductions up to 2.0 log. Moreover, enrichment of blueberries with *B. lactis* through the application of prebiotic coatings maintained quality and sensory characteristics for 14 days at 5◦C. These ready-to-eat fruits constitute novel, healthy and multifunctional alternatives of non-dairy probiotic foods that would allow meeting the current consumer demand. Besides, Bambace et al., (2024) studied a probiotic strain of *Lacticaseibacillus casei* added to alginate-based edible coatings enriched with inulin and oligofructose and applied to fresh-cut apple. *Lacticaseibacillus casei* was tested for its antagonistic effect against inoculated *Listeria innocua* and *Escherichia coli* O157:H7. It was reported that after 8 days of storage, high viability retention (more than 9.5 log CFU/g) of *L. casei* were detected in apple samples. The microbiological quality and nutritional properties were maintained by the use of active coatings, whereas the sensory quality decreased after 8 days of storage. A bactericidal effect was exerted by the probiotic strain loaded in the coating against *L. innocua* artificially inoculated on apple cubes; while *Escherichia coli* O157:H7 counts were reduced by 2.5 log after 8 days of refrigerated storage. Therefore, *L. casei* CECT 9104 and prebiotics, offering a promising alternative for the development of plant-based functional foods.

Khodaei et al., (2019) applied a new edible coating based on carboxymethyl cellulose (CMC) and *Lactobacillus plantarum* applied on fresh strawberries in order to study the impact on their shelf life at 4°C as well as on their physicochemical and microbiological characteristics. *Lactobacillus plantarum* exert a biocontrol effect, reducing the growth rate of molds and yeasts on the surface of treated strawberries compared to control samples.

In the same way, Mehrabi et al., (2024) aimed a study to evaluate the impact of combining edible gelatin coatings with lactic acid bacteria, and bifidobacteria on the quality, shelf-life, and sensory attributes of processed cooked chicken stored 45 days in cold conditions. Results indicate that lipid oxidation was reduced and weight loss was minimized in the coated samples compared to the control sample. The viable populations of bifidobacteria and lactic acid bacteria demonstrated good survival rates after 45 days of storage, with no significant differences in pH and water activity values between treated and untreated samples. The type of bacteria used in the coating did not significantly affect its performance in reducing oxidation, nor did the coating affect the crispiness of the chicken samples.

Conclusion

The food industry reported an increasing demand for green materials to produce new, environmentally safe and high-quality products. Biopolymers used in the food industry can replaced the conventional plastic-based packaging systems. Edible coatings and films obtained from natural polymeric materials represent a valuable alternative for food industry. Edible polymers shown as biodegradability and bio-environmental compatibility over non-biodegradable synthetic polymers. Biopolymers derived from agricultural, marine and animal sources have different applications based on their physicochemical properties, such as film-forming ability or entrapment of bioactive substances. Therefore, these polymers have found wide-spread applications in food industry. It also finds its applicability in the detection of food contamination and spoilage-causing bacteria, as well as functional food according to one's preference and/or nutritional needs.

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Industria ecológica: estudios de casos de compuestos poliméricos sostenibles exitosos

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