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REVIEW

Recent Advances of Edible Packaging as an Alternative in Food Packaging Applications

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The accumulation of non-biodegradable food packaging waste causes huge pollution to the environment, has become a major issue. Currently, the use of edible and biodegradable packaging for food applications to avoid the generation of waste is a fast-emerging eco-friendly technology with increased attention. The edible packaging; films and coatings synthesized from biodegradable sources like polysaccharides, lipids, proteins and composites can be consumed without disposing them to the environment. These can be used on different foods by functioning as barriers to moisture, vapours and other solutes, also by reducing lipid oxidation and discolouration. They perform multiple functions as carriers for active compounds and have the ability to release them at a controlled rate to the packed food, which significantly extends the shelf-life and hence, improves the quality of food. This review focuses on the recent researches on the innovative biopolymer-based edible packaging, an alternative to synthetic nonedible packaging.

Keywords: Food packaging, Biopolymer, Edible coating, Food safety.

INTRODUCTION

Currently, the accumulation of non-biodegradable conventional synthetic plastics is causing huge pollution to the environment, posing a threat due to high noxious discharges, changes in the carbon cycle and the inability to compost. This waste is in the form of a considerable quantity of solid waste in the urban areas; consequently, it leads to ever-intensifying ecological distress. Today, over 320 million tons of plastics are produced per year, where more than 40% are utilized as disposable packaging materials that produce an obvious source of waste [1]. This causes the topmost waste management challenge, signifying the importance of using eco-friendly raw materials to develop novel biodegradable and sustainable packaging materials. Thus, there is a requirement to promote environmentally friendly biodegradable polymers among people. Currently, edible and biodegradable coatings and films are a fast-emerging technology with increased attention among researchers and consumers, which act as alternatives to these synthetic nonedible plastic packaging.

Edible coatings or films can be introduced as thin layers of edible components, which are used in the primary packaging of food and consumed with the food itself. The major difference between edible films and coatings is that edible coatings are always coated on the product, whereas edible films are in the form of self-standing structures in nature [2]. A coating or a film may differ based on the method of application and the way it is presented. The application of an edible coating is done by dipping the food in the coating solution, which is in the form of a liquid, while edible films are originally produced as sheets and then employed as food wrappers [3]. Edible films are produced entirely using food-grade components and they are applied to food by spraying, electrostatic spraying and dipping, which produces a thin and uniform coating [4].

Currently, edible coatings and films have obtained significant attention in the food industry as a result of their advantages over non-edible, non-biodegradable films by maintaining the food quality. The key aim of developing edible coatings and films instead of synthetic packaging is that they are capable of consuming with packaged food. The barrier, mechanical, antimicrobial, sensorial properties and most importantly extend the storage life of various food products. They provide a semi-permeable barrier to prevent moisture and solutes migration through the film and also gases such as oxygen, carbon monoxide, carbon dioxide, *etc*. thereby decreasing the moisture loss, rate of oxidation and respiration [5]. In addition, they minimize the damage that occurs in minimal processing by reducing the surface browning, weight loss, softening, microbial growth, respiration and ethylene production [6].

At present, research studies are being carried out on multi-component edible films and coatings with two or more film-forming substances. These coatings and films have improved physical, mechanical and barrier properties. In order to achieve further improvements plasticizers, crosslinking agents and emulsifiers are being incorporated [7]. Other than that, films and coatings are formulated incorporating active compounds such as antioxidants, antimicrobial agents, anti-browning agents, flavours, colour agents and nutraceuticals to provide additional benefits such as antibacterial effects, antifungal effects and to increase the shelf-life of the packed food [8]. This review focuses on providing a broad update of the most recent advances of edible packaging as coatings and films for their future applications.

Classification of edible film-forming materials

The edible coatings and films that can be classified based on the structural material are presented in Fig. 1. Polysaccharide based coatings and films typically show lower barrier properties against moisture because of their hydrophilic but selective permeability to CO_2 and O_2 [9]. Some polysaccharides have the crystalline property, which causes processing and performance problems, specifically with the packaging of moist products. Besides that the polysaccharides produce constituents with high gas barrier properties [10]. These films can be produced from chitosan, cellulose, pectin and its derivatives, starch and its derivatives, seaweed extracts (agar, alginate, carrageenan), plant gums (tragacanth, acacia, guar) and microbial gums [11]. The linear structure of some polysaccharides such as chitosan and cellulose makes their films flexible, transparent, tough and resistant to oils [10]. Probably, more attention will be acquired in the future by the microbial polysaccharides for example curdlan, pullulan, xanthan and hyaluronic acid produced by bacteria and fungi [12].

Protein-based coatings and films are generally hydrophilic, liable to moisture absorption [12] and can be derived from sources of plants (soybean, wheat gluten, peanut, corn zein, cottonseed) or animals (whey protein isolate and concentrate, casein, gelatin, keratin, egg albumin, collagen). Protein-based films show poor water resistance, but they have good barrier and mechanical properties than polysaccharides [13]. They have become excellent oxygen barriers as a result of the association of polymers containing groups with hydrogen or ionic bonding [14].

Films and coatings based on lipids are good moisture barriers with reduced water vapour permeability because of their hydrophobic properties [15]. The lipids form more brittle and thicker films due to their hydrophobic nature [16]. In addition, lipid-based packaging can be used to minimize respiration, thus prolonging the shelf-life and enhancing the appearance by developing a surface sheen on fresh produce [17]. Lipid-based edible coatings and films can be produced utilizing varied lipid substances such as vegetable and animal fats and oils (coconut, palm, peanut, butter, lard, cocoa, monoglycerides, diglycerides, triglycerides and fatty acids), waxes (paraffin, candelilla, jojoba, carnauba, beeswax), essential oils (cinnamon, lemongrass, cloves) and extracts (camphor, mint, citrus fruits) [4,18].

Properties of edible coatings and films: A coating or a film must meet specific requirements for its legality, safety and performance. Successful application of coating requires to spread uniformly, dry fast, not foam and easy to peel-off from equipment [19]. They must be water-resistant; thus, they remain intact when applied and melt above 40 ºC without decomposition. Edible coatings and films have to be translucent to opaque and capable to endure minor pressure. Once applied, a coating should not be cracked, discoloured, or peeled during handling or storage, including when it contacts the condensate. It should be simply emulsifiable, should not be tacky or adhere to packaging and have effective drying properties. Further, it must not adversely react with the food and not change the sensory quality. Coatings and films should permit or limit the exchange of carbon dioxide, oxygen gases, aroma volatiles and

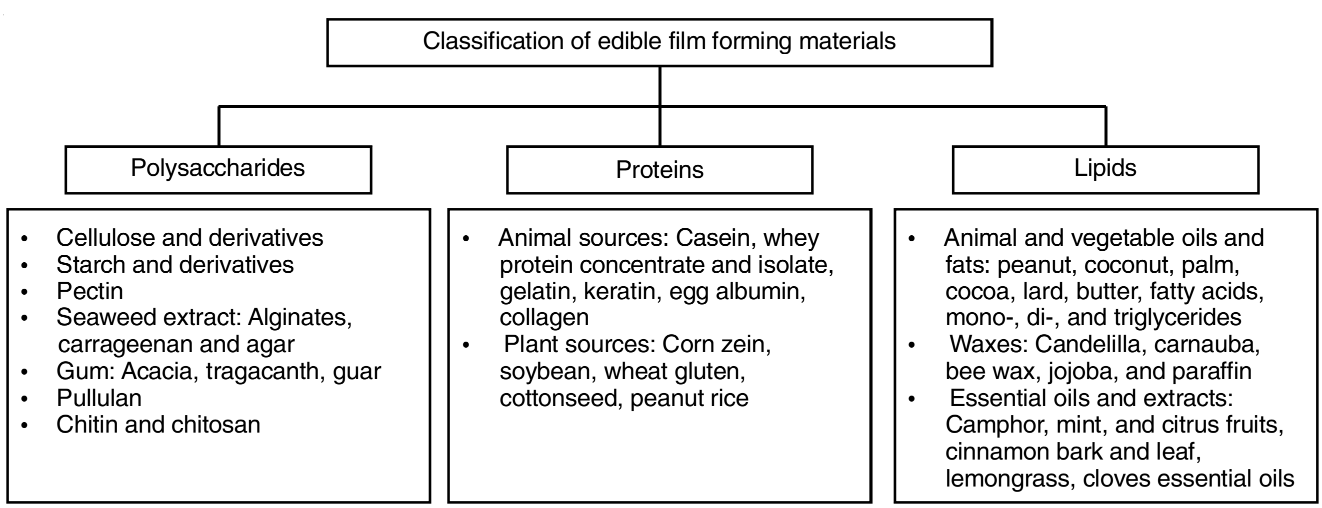

Fig. 1. Classification of edible packaging according to their structural material [3,8,10,11]

water vapour. In case of fruits, they should permit enough gas exchange (minimum of 1-3% oxygen) to prevent the anaerobic respiration of fruits but provide enough restriction to retard the senescence and ripening while delaying the loss of vapour to avoid shrivelling [20]. For fatty food products, the coating should be an oxygen barrier to prevent rancidity. Films and coatings should improve the appearance and mechanical properties, preserve structural integrity, retain volatile flavour compounds and convey active ingredients (vitamins, antimicrobial agents, antioxidants, *etc.*) [12]. Often coatings may be able to impart a luster to the product and colour that must last throughout shipping, product handling and marketing [21].

Importance of edible packaging: Food additives such as antioxidants, antimicrobials, flavour compounds, colourants and probiotics are very sensitive to external environmental factors such as light, oxygen and temperature, whereas, food processing and storage often involve undesirable environmental conditions. In this situation, films and coatings have become helpful in providing protection against the environment, enhancing solubility and monitoring compound release. Similarly, the bioactive compounds introduced into edible packaging are protected by a solid barrier developed between the additive and environmental conditions [22]. Some of the bioactive compounds such as antioxidants and vitamins are adversely affected by ultraviolet light and the edible packaging may form a shield against ultraviolet radiation [23].

Oxygen which is responsible for microbial growth, lipid oxidation, browning reactions and loss of vitamins causes the major quality loss of the packaged foods [24]. The fat oxidation results in the nutrient loss and development of off-flavours, off-colours and off-odours [25]. The selection of packaging with limited oxygen permeability and inclusion of strongly flavoured antioxidants in edible coatings and films allows for their encapsulation [21] and can reduce their strong aroma [26].

Edible packaging is capable of monitoring the release of the bioactive compound by controlling the pH, temperature, humidity and mechanical rupture of the system and they become more advantageous in their application [27]. Edible packaging including coatings and films can be utilized as functional materials to help successfully overcome many difficulties that occurred in the marketing of foods. Those problems can be solved by delaying the migration of gas, moisture, oil and solute, improving structural integrity and conveying food additives [4]. In addition, by decreasing the occurrence of hiding scars, physical damage and improving surface sheen they enhance the appealing appearance of the coated foods [4].

Concerning the fresh produce industry, the moisture barrier properties of edible biodegradable coatings and films help to avoid weight loss/gain and variations in appearance, texture and flavour during postharvest storage. They act as an adequate barrier to gas for monitoring the exchange of gases between the packaged food and its surrounding atmosphere, which would retard deterioration, avoid the enzymatic oxidation and respiration, prevent the fresh fruits and vegetables from texture softening and browning discolouration throughout postharvest storage. They are used to retain the natural volatile colour and flavour compounds from fresh produce by limiting their exchange. They also reduce the microbial loads and improve the product quality by acting as carriers of other functional components [28].

The global usage of packaging materials shows a gradual increase of 8% annually. Tavassoli-Kafrani *et al.* [29] reported that below 5% of all plastics used in packaging are mostly being recycled, resulting in a higher plastic accumulation in the environment. Besides, growing consumer considerations on food safety are directed to the improvement of biodegradable and edible packaging in the food industry [30]. The edible film-coated food products can be consumed as it is without releasing the non-biodegradable cover, into the environment that would lead to pollution.

Film-forming procedures: The edible film is usually covered over the surface of a food product as a solid matrix and acts as a primary packaging being flavourless, colourless and not interfering with sensory qualities of the food product [31]. An edible film can further be used as sachets or pouches, mostly for ready-to-drink beverages and meal replacements, which would release its content and disappear when added to cold or warm liquids [18]. The edible films can be synthesized by two different methods from edible materials *viz.* dry and wet processes, also called extrusion and solvent casting methods, respectively [32]. The solvent casting method involves the use of different solvents for the film development and involves the spreading of the film-forming solution onto a smooth surface and drying at controlled conditions for solvent evaporation and film development. The most commonly used dry methods of production of edible films are injection, extrusion, blow-molding and heat-pressing processes [4]. The application of thermal processes has increased for edible film development due to the combination of efficiency and high productivity [33]. However, the concentration and functionality of some active components in the film-forming solutions may be affected by the higher temperatures used in the dry processes [34]. The ultimate characteristics of the developed packaging material will be depending upon the selected processing method.

Wet processing: Usually, wet processes are comprised of four steps *viz*. dispersion, homogenization (mixtures or emulsions), molding or casting and drying [9]. An additional mixing step is essential in developing composites to acquire homogeneous and stable film-forming solutions if dissimilar hydrocolloids or further incompatible components are combined. Table-1 recent trends in active edible film development (wet method) highlights the trends in edible coating and film development based on the wet chemical method.

Initially, mixing of all components is required to obtain homogeneous edible coatings and films. Proper film-forming solutions can be achieved through low-speed stirring [35-37], the combination of stirring and ultrasound cell disruption [38], moderate speed stirring [35,39], high-speed stirring [35,40,41] and high-pressure microfluidization [42]. As the ultimate product must be biodegradable and edible, the film preparation is done by using water and other food-grade solvents such as ethanol [4,43]. Furthermore, to yield edible films without phase separation, the film-forming solutions must be homogenized to

TABLE-1
RECENT TRENDS IN ACTIVE EDIBLE FILM DEVELOPMENT (WET METHOD)

Biopolymer	Solvents	Additives	Homogenization conditions	Drying conditions	Ref.
Chitosan	Acetic acid (1%)	Rosemary essential oil (EO) and Tween 80	Chitosan solution stirring for 20 min at 90 °C, cooling to 40 °C; mixing with Tween 80 for 30 min and adding EO (Ultra Turrax, 2 min, 4000 rpm), cooling, degassing (5 min)	72 h at 25 °C on a Teflon coated steel plate	[152]
Chitosan	Acetic acid (1%)	EOs and Tween 80	Chitosan solution stirring at 45 °C, 250 rpm overnight, homogenizing for 4 min at 2500 rpm	48 h at 22 °C and 30% RH on a dish	[48]
Cassava starch	Water	Glycerol and cellulose fibers	Hydration of fibers (24 h); stirring at 14,000 rpm for 10 min; mixing and stirring all contents for 5 min at 71 °C and 90 rpm); tape casting (spreading speed 40 cm/min)	60 °C for 5 h in Polymethyl methacrylate protected by a silicone-coated PET film	[61]
Sodium alginate	Water	Glycerol and EO surfactant	Stirring sodium alginate solution for 1 h at 100 °C, cooling, mixing with EO and glycerol and vortex	Ambient conditions on a glass dish	[153]
κ-Carrageenan	Water	Glycerol, EOs and Tween 80	Stirring at 82 °C for 15 min), mixing with glycerol, continue stirring at 82 °C, for 25 min	At 30 °C for 30 h on a glass dish	[136]

evenly distribute all the miscible and non-miscible compounds in solvents and emulsifiers can also be added. Food-grade plasticizers such as glycerol, polyethylene glycol, or sorbitol are used to improve the uniform distribution of film-forming solutions and reduce the polymer brittleness and rigidity. Active ingredients incorporated into water-soluble film-forming polymer solutions by direct addition followed by the casting method [44,45], nano-emulsions through ultrasonication [46] and encapsulation of active ingredients into nanoliposomes [47] have been described.

After mixing and homogenization, polymer solutions are cast on flattened plates or molds and left to dry under controlled conditions. The most common technique of synthesis of edible films is the casting method. Further, other film-forming procedures, such as blown-film extrusion, slot-die extrusion and calendaring those involved in higher temperatures, leading to undesirable reactions result in the degradation of biopolymers as well as nutritional and sensory losses in fruit/vegetable compounds [19]. The removal of the film from the plate surface after casting will be facilitated by varying the surface energies in the interface of the plate surface and the film [4]. Therefore, diverse materials, such as glass [44,48], polystyrene [8,49], polyethylene [50], polycarbonate [51], methacrylate [47] have been used depending on the polymer to get films by casting.

To have better properties in the final product, blending is done using a direct method or related to co-drying processes [9]. The combination of polysaccharides with proteins and active compounds is done to produce edible films and coatings, taking advantage of their synergistic effects [50,52]. Edible chitosan-based films with gelatin [53,54] or methylcellulose [55] were formed targeting the structural, mechanical and antimicrobial properties.

Dry processing: The extrusion, blow molding, injection and heat pressing are the mostly used dry processing methods for developing edible films [9]. The mechanical and thermal energies are involved in developing extruder-based edible films [56]. The key benefits of the extrusion method are the low processing time and energy-efficient in contrast to the casting method and improved optical and mechanical properties such as transparency and elongation of edible film, respectively [57-59]. The twin-screw extrusion produces high temperature and pressure to interrupt the polymer particles and blend the film constituents has improved the application of extrusion procedure for edible film production [60]. Further, film-blown die, thermopressing and injection molding [61] are combined with extrusion to yield the ultimate edible films [62,63]. The thermal and mechanical variations in the constituents based on starch have resulted in significant changes in physico-chemical properties [64]. The extrusion technique is suitable to acquire even thermoplastic starch constituents, in various shapes, threads and films at 80 rpm nevertheless with higher retrogradation of starch, while the fragmented starch constituents were acquired at 40 rpm and 120 rpm [65].

Application methods of edible coatings on food

Dipping method: Due to the low cost, simplicity, good coverage on uneven food surfaces and ability to form a thick coating, the dipping method has become the most common lab-scale technique in the coating of food products [29]. In the dipping technique, the food product is immersed in film-forming solutions, dripping off the excess and allowing it to air dry resulting in a thin film formation surrounding the food product. However, this method may lead to microorganism growth in the dipping tank [66].

Spraying method: This method is suitable for foods that are to be coated with low viscosity coating solutions, by simply spraying with the aid of nozzles at high pressure (60-80 psi) [67]. Due to the high spraying pressure exerted by the nozzles, this technique requires a low quantity of coating materials to complete uniform coverage [67]. In addition, this method is useful to achieve a smooth coating, thickness control, prevention of coating solution contamination, control the temperature of the solution and has the possibility of multilayer applications while enabling of working with large surface areas [68].

Electrostatic spraying: The advantages of the electrostatic spraying technique are producing homogenous distribution, controlling the droplet size, increasing the droplet coverage and deposition and reducing the wastage of coating solutions [29].

New trends in polysaccharide-based edible packaging: Polysaccharides are the polymers that occur naturally and broadly used to formulate edible packaging, including cellulose, pectin, starch and their derivatives, gums, pullulan, seaweeds (alginate, carrageenan and agar) and chitosan [69]. The recent advances of polysaccharide-based edible coatings and films are listed in Table-2.

Cellulose and derivatives-based coatings: In addition to cellulose (poly-β-(1→4)-D-glucopyranose), cellulose derivatives namely hydroxypropyl methylcellulose, methylcellulose and ionic carboxymethylcellulose are also generally utilized in the development of commercial edible films and coatings. The lignocellulosic materials are also highly appropriate in the field of manufacturing edible films. Slavutsky & Bertuzzi [70] have described the effective development of starch-based edible films incorporated with nanocrystalline cellulose extracted from sugarcane bagasse. Lustrous and clear films, which have similar attributes to those of xylan were synthesized with hemicellulose portions obtained from the *Pinus densiflora* leaves with high possibility as edible films [9]. The edible films produced from cassava and potato starches, strengthened with reinforcement agents such as cellulose fibers and/or nano clay, were developed and evaluated by El-Halal *et al.* [71]. They concluded that the addition of reinforcement agents in the developed films produced more resistance and the films have shown increased tensile properties while decreasing the water vapour permeability. In deep frying food products, methyl cellulose and its derivatives have been widely employed in order to obstruct oil absorption [72]. The composite coatings and films comprised of bee wax and fatty acids have also been developed [73]. Composite films which have improved optical, mechanical, water vapour barrier properties and thermal stability were synthesized incorporating crystalline cellulose nanofibrils separated by acid hydrolysis from cotton linter [74]. Alginate film composites were produced from alginate-carbohydrate film-forming solutions carrying 5% (w/v) alginate, 0.25% (w/v) pectin, cellulose, carrageenan, modified or unmodified potato starch or gellan gum [75]. Alginate-based composite films incorporated with cellulose extracted from soybean husks have shown similar mechanical properties to those synthesized from commercial microcrystalline cellulose.

Starch and its derivatives based coatings: Starch is the key polysaccharide has potential to be used in the preparation of biodegradable and edible films. Among starches, wheat, cassava and corn starches have been recently utilized to formulate edible coatings and films due to their biodegradability, bioavailability, biocompatibility, non-toxicity and relative cost-effectiveness. Starch is usually used in combinations with several materials such as soy protein concentrates [76], modified and native cassava starches [77], wax and normal starches [78], wheat starch and rapeseed oil [79], wheat starch and whey protein isolates [80] and glycerol, stearic acid, cassava starch and carnauba wax [81]. A study done on films based on different native starches, such as cassava, potato and rice starch, mixed with plasticizers such as sorbitol and glycerol and montmorillonite clay for their physical properties showed the high potential in coating application for food products. It was found that rice starch films had low water solubility and higher elongation values when compared to cassava and potato, starch based films [82]. Starch-based coatings were developed for the application on 'Brussels sprouts' to extend the shelf-life by enhancing surface colour, texture and minimizing weight loss. The coatings were synthesized formulating with an aqueous solution of sodium hydroxide, sorbitol, glycerol and sunflower oil as functional ingredients [83]. To improve the antimicrobial

TABLE-2
RECENT TRENDS IN POLYSACCHARIDE-BASED EDIBLE PACKAGING

Polysaccharide	Major composition	Food product	Significant functions	Ref.
Cellulose	Cellulose derivatives (hydroxypropyl methylcellulose, methylcellulose) coatings with sorbitol additives.	Potatoes	Reduced oil uptake in fried products	[154]
Cellulose	Hydroxypropyl methylcellulose, beeswax with glycerol and oleic acid	Cherry tomatoes	Improved the respiration rate, weight loss, fruit firmness, peel colour and sensory attributes	[109]
Starch	Corn starch, polyvinyl alcohol, polyurethane, natamycin	Semi-hard cheese	Controlled the development of the mold on cheese surfaces	[155]
Chitosan	Chitosan, green tea extract, gallic acid, glycerol additives	Walnut kernel	Improved the sensory properties, reduced lipid oxidation and fungal growth	[156]
Chitosan	Chitosan, gelatin, glycerol additives	Beef	Reduced lipid oxidation and enhanced colour preservation during retail display	[157]
Chitosan and pectin	Chitosan, pectin, trans-cinnamaldehyde, β-cyclodextrin hydrate additives	Fresh-cut cantaloupe	Shelf-life extension of cantaloupe stored at 4 °C.	[158]
Pectin	Pectin, green tea extract, polyethylene glycol additives	Pork patty	Better maintenance of physicochemical, microbiological and sensory properties	[159]
Pullulan	Pullulan, α-amylase, glutathione, ethanol additives	Apples	Better preservation of appearance, colour, sensory attributes during storage	[160]
Alginate	Alginate and distilled water	Microwaveable food	Increasing warming efficiency	[161]
Alginate	Polycaprolactone, alginate, antimicrobial compounds	Broccoli	Prevention of the growth of pathogens	[162]
Carrageenan	κ-Carrageenan/chitosan/mustard extract/allyl isothiocyanate	Fresh chicken breasts	Inhibition of the growth of *C. jejuni*, aerobic bacteria and lactic acid bacteria	[163]
Carrageenan	κ-Carrageenan	Encapsulating aroma compound	Effective in flavour encapsulation	[164]

activity of chicken sausages, coatings based on starch added with D-glucose, EDTA, silver nitrate and trichloroacetic acid have been used [84].

Pullulan-based coatings have the possibility for maintaining the freshness of strawberries and kiwifruits due to their good moisture and gas barrier properties [85]. Therefore, it is a superior material for coating fruits and vegetables possessing elevated respiration rates, hence avoiding or delaying respiration and oxidation of coated food products [85]. The application of pullulan-based coatings and films incorporated with chitooligosaccharides and glutathione have shown improvements in the shelf-life of various fruits and vegetables [69]. Today, researchers have focused on the effect of the pullulan-based edible coatings in combination with various additives such as antibacterial and anti-browning agents for minimally processed foods to extend their shelf-lives [86].

Carrageenan: Carrageenan, another common polysaccharide extracted from *Chondrus crispus* [87] is used as a coating material for fruits and vegetables. The studies have proven that carrageenan-based coatings are capable of increasing the shelf-life of fruits and their fresh cuts. A coating formulation has been developed by dissolving a desired weight of carrageenan in distilled water and incorporating different concentrations of glycerol as a plasticizer ranging from 0-1% w/v. It has been found that the formulation of carrageenan and glycerol at concentrations 0.78% (w/v) and 0.85% (w/v), respectively, is the best formulation considering the firmness and colour component of coated and uncoated fruits [88]. The incorporation of antioxidant or antimicrobial agents in carrageenan based film composites helps to extend the quality life of perishable foods by protecting against enzymatic browning, microbial growth, vitamin losses and oxidation [89]. All of κ-, ι- and λ-carrageenan based film-forming dispersions with green tea extract incorporations applied for blueberries and raspberries can extend the shelf-life of blueberries and raspberries under refrigerated conditions, promoting the better appearance and preserving their firmness to a greater extent. The green tea extract addition in the film-forming solutions has enhanced the antiviral activity for hepatitis A virus (HAV) and murine norovirus (MNV) at both refrigerated and ambient temperatures in blueberries and raspberries [90]. Intelligent packing films which are pH-sensitive with enhanced antioxidant activity have been developed to determine the freshness of milk using κ-carrageenan by incorporating mulberry polyphenolic extract, which possesses a high anthocyanin content that can change their colour in different pH values. The properties such as thickness, the barrier to UV-visible light and water vapour, pH-sensitivity and antioxidant properties of the κ-carrageenan film have been significantly enhanced by incorporating phenolic mulberry extract [91]. Liu *et al.* [91] have stated that the film added with high anthocyanin content helps to indicate the freshness of foods such as fish, meat and shrimp by becoming sensitive to the pH changes and it acts as a visible pH-sensing label. Also, by imparting antioxidant properties through the release of phenolic compounds into the packed food products, it extends the shelf-life of the packed food becoming an active packaging material.

The seaweed *Mastocarpus stellatus*, a good source of hybrid carrageenan, which is a substitute to commercial κ-carrageenan has been used in formulations [92]. The recently studied seaweed based edible packaging materials are recorded in Table-3.

Chitosan: Chitosan is formed by chitin, which is present in the exoskeleton of mollusks and crustaceans. The process involved in extraction is alkaline deacetylation [9]. Chitosan based edible film composites have been developed in combination with various biopolymers, such as starch [93], fish gelatin [41] and proteins synthesized from zein [94] have been studied recently. The use of partially processed chitosan with a shrimp (*Litopenaeus vannamei*) protein concentrate has shown promising potential in the active edible packaging industry with enhanced antimicrobial and antioxidant effects [52]. The cinnamon essential oil incorporated chitosan films were able to have good antimicrobial, antioxidant properties and mechanical properties such as elongation at break, in addition to the decrease in solubility in water, moisture content and water vapour permeability [95].

New trends in protein based edible packaging: These films and coatings are well-proven to offer several benefits such as minimizing the moisture and aroma loss due to excellent barrier properties. The film composition is vital to detain the solute migration and reduction in inter-component moisture in foods. Furthermore, the coatings based on proteins can be used in multilayer food packing materials composed of non-edible films or among diverse layers of components in diversified foods [96]. The recent advances in edible packaging developed from the commonly used proteins are listed in Table-3.

Milk protein based films: Whey proteins and casein are the milk proteins that are used in formulating edible packaging. Milk protein-based films show moisture barrier properties higher than those of corn zein films but similar to those of wheat gluten and soy protein films [96]. Nevertheless, these coatings exhibit excellent barrier properties to aroma compounds and oil [97]. The plasticizers such as sorbitol and glycerol have been used to decrease the permeability essentially, water/vapour of casein and whey protein-based films while improving the film flexibility. The plasticizer concentration may influence the increase of the film thickness, tensile strain and water vapour permeability, but for the reduction of tensile strength and elastic modulus [97]. In addition, their barrier properties can be enhanced by combing with many lipids such as waxes [98], plant oils [99], acetylated monoglycerides [100], or fatty acids [101]. It was reported that the coatings developed from whey protein isolate and caseinate can be efficiently used to slow down the browning of potatoes and minimally processed apples by acting as barriers to oxygen [102]. Also, those coatings help to minimize dehydration, while retaining the firmness of carrots when packed in combination with modified atmosphere [103].

Gelatin: Gelatin based films were found to be the broadly studied edible packaging among entire protein based films by becoming a good barrier to light, gases and oil migration; but, limiting their application due to high water vapour permeability [17]. Gelatin-based films can be developed from 20-30% (w/v) gelatin, 10-30% (v/v) plasticizer (glycerol), water and drying

TABLE-3
RECENT TRENDS IN PROTEINS-BASED EDIBLE PACKAGING

Protein	Composition	Food product	Significant functions	Ref.
Milk protein	Whey protein concentrate, pullulan, beeswax, glycerol	As a film	Concentration-dependent film thickness, water vapor permeability (WVP) and tensile elongation	[165]
Milk protein	Whey protein isolate, guar gum, sunflower oil, lactic acid, natamycin, glycerol, Tween 20	Semi-hard cheese	Decreased changes in hardness, water loss and colour, high antimicrobial activity	[166]
Gelatin	Gelatin, chitosan and procyanidin	Fish, meat, cheese	High antioxidant, antimicrobial activities	[167]
Gelatin	Fish gelatin/pomegranate (*Punicagranatum* L.) seed juice by-product	As a film	Increased water resistance and film stiffness, decreased elongation and transparency, inhibition against *S. aureus and* high thermal stability	
Collagen	Collagen, sodium alginate, glycerol, glutaraldehyde	As a film	Decreased elongation, high thermal stability, viscosity and tensile strength,	[168]
Collagen	Collagen, chitosan	Nutraceutical products	Higher elongation, antioxidant and UV barrier properties, lower water solubility, tensile strength and lightness	[169]
Zein	Zein, corn-wheat starch solution, sorbitol, citric acid, a mixture of carboxymethyl cellulose and sodium alginate	As a film	Increased elongation at break, tensile strength, contact angle, moisture content, colour, thickness and antioxidative properties	[170]
Zein	Zein, chitosan, essential oils (cinnamon, anise, orange)	As a film	Excellent mechanical properties, reduced WVP and inhibition of the growth of *Rhizopus* sp., *Penicillium* sp.	[171]
Gluten	Gluten, zein, rennet casein, potassium caseinate, locust bean gum, xanthan gum additives.	Trout fillets	Enhanced sensorial, physical and biochemical qualities	[172]

the film-forming solution at controlled conditions [45]. These were further developed for increasing their barrier and mechanical properties by incorporating functional ingredients such as chitosan, sunflower oil, corn oil, *etc.* [104]. The addition of gelling agents such as κ-carrageenan and gellan helps to increase the tensile properties, barrier properties and melting point of gelatin based films against water vapour; but resulting in the films being darker [105]. The use of nanotechnology has become a trending approach to optimize the aforementioned properties of gelatin based films. As reported in another study, the addition of sodium montmorillonite nano clay (MMT) to yield gelatin nanocomposite films is effective in enhancing the moisture resistance by becoming a barrier to water vapour without influencing the film transparency [106].

Soybean proteins: Soy proteins that have inherent hydrophilicity result in poor resistance to moisture and low water vapour barrier properties in the developed films but exhibit potent barriers against oxygen, particularly in low relative humidity environments [16,49]. Thus, plasticizers and hydrophobic compounds such as lipids are incorporated into soy protein-based films to balance the water vapour barrier properties and mechanical properties like tensile strength [17]. Thus, it has changed the film microstructure with total colour differences and high opacity [107].

Corn zein: Corn zein has improved film forming properties due to its hydrophobic performance, thermoplastic and excellent barrier properties, thus it is applicable for the fabrication of edible and biodegradable films. Several studies on the zein films and coatings have proved their properties as a carrier of essential oils, natural antimicrobial enzymes such as glucose oxidase and lactoperoxidase, lysozymes, bacteriocins and natural antioxidants. High performance was achieved by the lysozyme incorporated zein-based films for the inhibition of Gram-positive bacteria, *e.g.*, *Listeria monocytogenes* [108]. Plasticizers have been incorporated in the preparation of zein coatings and films to increase flexibility by reducing brittleness [108].

New trends in lipids-based edible packaging: The requirement to decrease the loss of moisture from packaged or non-packaged food can be accomplished by using lipids as candidates for edible coatings and films due to their non-polar nature. The most frequently used lipids in edible packaging are highlighted in Table-4. The lipids that are most extensively used to synthesize edible packaging include edible waxes such as paraffin, candelilla, carnauba, bee wax, herbal wax, fatty acids, triglycerides, acetylated monoglycerides and fatty alcohols, edible resins include terpene and shellac resins. Due to the hydrophobicity of lipids, the lipid-based films or coatings have become thicker and much brittle and enhanced water barrier and tensile properties. However, it was described that films or coatings containing lipids might impair the physical appearance and surface sheen of the coated food products [109]. The lipid-based edible films synthesized from hydrocolloids such as alginates and starch can be used as packaging for fresh fruits, vegetables and baked products. Yet the market size is very small due to the difference in prices compared to commercial synthetic packaging, the benefits they offer such as biodegradability, selective permeability, high mechanical properties and quality maintenance of the foods may generate high consumer acceptance [110].

Recent advances in designing nano-biocomposite edible packaging: In fact, the biopolymers are hydrophilic, enhancement of moisture barrier properties is the major challenge in

TABLE-4
RECENT TRENDS IN LIPIDS-BASED EDIBLE PACKAGING

Lipid	Composition	Food product	Significant functions	Ref.
Candelilla wax	Candelilla wax coating with mineral oil, mesquite gum	Guava fruit	Enhanced texture, reduced gloss, weight loss, emission of ethylene, retention of colour	[127]
Candelilla wax	Candelilla wax, guar gum and glycerol additives	Strawberry	Enhanced antifungal properties to extend the postharvest shelf-life.	[128]
Carnauba wax	Cassava starch, carnauba wax, glycerol and stearic acid	Fresh-cut apples	Reduced water vapor permeability and weight loss	[81]
Beeswax and carnauba wax	Gelatin, glycerol, beeswax, or carnauba wax	As a film	Enhanced antioxidant, barrier and thermal properties	[129]
Lauric acid	Flaxseed gum, lauric acid and oligomeric procyanidins	As a film	Improved mechanical and barrier properties	[130]

the synthesis of edible biopolymer based packaging. But the defects can be overcome by the use of nanocomposite technology which adds interesting characteristics to food packages. Recent advances in designing nano-biocomposite edible packaging are listed in Table-5. In case of polymer/clay nanocomposites, nano-biocomposites including biopolymers and clay is one such novel and significant developments in food packaging technologies. The incorporation of several nanoparticles such as titanium dioxide (TiO_2), silicon dioxide, silicate nanoplatelets, nano clays, carbon nanotubes, graphene, chitin nanoparticles, starch nanocrystals, cellulose nanofibers (CNF), chitosan nanoparticles improves the total functioning of the edible packing material with significant enhancement of the expected properties [111]. Recently, the different types of nano-fillers and biopolymers such as montmorillonite, silver and ZnO have been incorporated into the biopolymers such as polylactic acid (PLA) and starch which makes a novel approach to develop biocomposite materials with better-quality properties and performance for edible food packaging purposes [112]. It was concluded that the shelf-life of Indian olives (*Elaeocarpus floribundus Blume)* can be enhanced by guar gum nanocomposite-based edible coatings. Specifically, 1.5% (w/v) of guar gum concentration was effective in slowing down the changes that occur in the physico-chemical properties of fruit during the storage [113]. In another study, an edible film composed of the nanocomposite synthesized using pectin and clove essential oil nanoemulsion was used to acquire desirable improvements in mechanical properties, water vapour barrier properties and antibacterial activity against *Staphylococcus aureus* and *Escherichia coli* [114].

Mangiacapra *et al.* [115] described the ability to minimize the oxygen diffusion in pectin-based edible films through the incorporation of montmorillonite clay into the packaging complex. Yildirim *et al.* [116] also developed nanocomposites prepared by gelatin and montmorillonite and reported that the intercalation with montmorillonite could significantly enhance the thermal properties of gelatin, while the mechanical properties of the composite can be improved notably due to high barrier properties exhibited by montmorillonite.

Recent developments in the active edible packaging applications in the food industry: An active edible packaging involves the careful incorporation of functional ingredients to release or absorb specific compounds from or into the packed food or its surrounding environment [116]. This novel approach helps to maintain or extend the storage life of foodstuffs, thus confirming their safety, quality and reliability. Active packaging can be categorized into active scavenging systems, those able to remove the undesired compounds such as moisture, gases (oxygen, carbon dioxide), odor, or ethylene from the food or its surrounding environment and active-releasing systems

TABLE-5
RECENT ADVANCES IN THE DEVELOPMENT OF EDIBLE NANO-BIOCOMPOSITE PACKAGING

Package components	Additive	Improved properties	Ref.
Carboxymethyl cellulose, starch polysaccharide matrix	Cellulose nanocrystals	Improved optical transparency and tensile properties, reduced WVP	[131]
Chitosan-gelatin nanocomposite	Silver nanoparticles, polyethylene glycol	Improved mechanical properties and decreased light transmittance in the films and shelf-life extension of the film applied red grapes	[132]
Gelatin/ZnO nanoparticle nanocomposite	Glycerol	Increment of water vapor barrier properties, improvement of antimicrobial potential against *L. monocytogenes* and *E. coli* and shelf-life extension of film applied white soft cheese	[133]
ZnO nanorods, gelatin composite	Clove essential oil	Enhancement of antimicrobial activity against *S. typhimurium* and *L. monocytogenes*, reduction of hydrophobicity, the shelf-life extension of peeled shrimps	[134]
Starch-cashew tree gum nanocomposite	Montmorillonite-nanoclay	Improved water vapor barrier property, reduced oxidation of cashew kernels, protection against moisture loss	[135]
κ-Carrageenan and nanoclay based film	*Zataria multiflora* essential oil	Advanced mechanical, antimicrobial and water vapor barrier properties	[136]
Chitosan, κ-carrageenan, alginate, nanocomposite	Cellulose nanocrystals and microfibers produced from alfa fibers	High flexibility and mechanical properties	[137]

that can release active compounds for example antioxidants, antimicrobial compounds, flavours, ethylene, carbon dioxide, or ethanol to the packed food or into its headspace. In addition, to meet the packaging requirements, edible packaging can be further employed in the supply of bioactive substances, minimization of oxidation of food and microbial deterioration. Some potential active edible packaging systems for food applications are described below:

Carriers of antioxidants and antimicrobial agents: The advancement of antimicrobial and antioxidants rich edible packaging in food applications has obtained increased attention in recent years. Though there have been broadly used synthetic antioxidants, such as propyl gallate, butylated hydroxyanisole and butylated hydroxytoluene in food packaging technologies to avoid lipid oxidation, now there is a rising demand for the addition of natural antioxidants for example plant extracts, polyphenols, essential oils and tocopherols in active packaging systems. Antimicrobial food packaging systems have the potential to inhibit the growth of pathogenic and spoilage microorganisms. Edible packaging with antimicrobials or antioxidants possibly will decrease the requirement for the addition of preservatives by monitoring the migration of active ingredients at the food surface. Some recent advances in the application of antioxidants and antimicrobial agents in active food packaging are listed in Table-6.

Films with high antioxidant activity found from green tea extract, which contains a high amount of bioactive compounds have been proven to enhance the oxidative stability of pork meat products [117]. In addition, the multilayer barrier films containing oregano essential oil exhibited higher antioxidant activity than those with green tea extract by avoiding the lipid oxidation of foal meat packed in modified atmosphere packaging methods (MAP) [118]. It was reported that the methanolic extracts of the seeds, stem and leaves of *Pistacia terebinthus*, which contain numerous phenolic compounds will provide antimicrobial and antioxidant properties to chitosan based films [119]. The alginate-calcium crosslinked coatings incorporated with cinnamon (*Cinnamomum zeylanicum*) and nisin have been used to extend the shelf-life of northern snakehead fish fillets stored under refrigeration conditions (4 ± 1 ºC) due to the antimicrobial activity of nisin and cinnamon in addition to the antioxidant activity of cinnamon [120]. Sweet whey, which is used as the base for the antimicrobial edible coating preparation has shown improved physico-chemical, microbiological and sensory attributes of Swiss cheese due to antibacterial function provided by the presence of the lactic acid [121]. Currently, some other antimicrobial agents added in edible packaging coatings and films preparation that function against Gram-positive and Gram-negative bacteria include lauric arginate ester, allyl isothiocyanate and nisin peptide [17].

Carrier of probiotics: At present, the consumption of probiotics rich food products has become a novel trend worldwide concerning healthy diet and well-being. This approach has acquired a high interest from the food and beverage industries, targeting the production of novel probiotic foods and from researchers in developing novel bioactive food systems that deliver probiotics and other possible applications. The incorporation of probiotics such as species of *Lactobacillus* and *Bifidobacterium* most commonly, *Escherichia coli*, the yeast *Saccharomyces boulardii* and some *Bacillus* species-rich edible coatings and films in food products has become an efficient way to supply the daily required probiotics to the consumers [17]. The antimicrobial substances produced by the probiotics and their competition will significantly help to enhance food safety and stability by monitoring the development of spoilage microbes. Recent advances regarding the encapsulation of probiotics in edible packaging are presented in Table-7.

Many types of researches were done based on the integration of probiotics using various media in edible packaging. The incorporation of lactic acid bacteria (LAB) who produce antifungal peptides into edible films and coatings exhibits antimicrobial features and ensures the microbiological safety of the food products due to the antimicrobial effects of LAB [122]. The carboxymethyl cellulose-based films incorporated with probiotics such as *Bifidobacterium bifidum*, *Lactobacillus acidophilus, Lactobacillus casei* and *Lactobacillus rhamnosus* have shown increased moisture barrier properties and opacity, but low mechanical properties. Furthermore, the viability of

TABLE-6
RECENT ADVANCES IN EDIBLE PACKAGING INCORPORATED WITH ANTIOXIDANTS AND ANTIMICROBIAL AGENTS

Package components	Antioxidant/antimicrobial agent	Properties improved	Ref.
Chitosan	Chitosan-nanoparticles	Improved antimicrobial properties	[138]
κ-Carrageenan	Montmorillonite, nanoclay and essential oils from *Zataria multiflora Boiss*	Improved mechanical and antimicrobial properties	[136]
Sweet potato starch	Montmorillonite, nanoclay, thyme essential oil	Well-preserved sensory profiles, efficient inhibition of *S. Typhimurium* and *E. coli*, better microbiological quality of baby spinach under refrigeration conditions	[139]
Cassava starch/chitosan	Pitanga (*Eugenia uniflora L.*) leaf extract, natamycin	Alteration in physicochemical and microstructural characteristics of films, decreased film elongation and tensile strength, higher anti-fungal activity on natamycin rich films, enhanced antioxidant properties of films incorporated with pitanga leaf extract	[140]
Chitosan	Kombucha tea	Developed water vapor barrier properties, UV protection and antioxidant activity, efficient retardation of microbial growth, lipid oxidation and shelf-life extension of minced beef meat	[141]
Alginate	Ascorbic acid citric acid	Contributed to the colour retention while maintaining nutritional, physicochemical properties and antioxidant potential of fresh-cut mangoes	[142]

TABLE-7
RECENT ADVANCES IN ENCAPSULATION OF PROBIOTICS IN EDIBLE FILMS AND COATINGS

Matrix composition	Probiotics	Food application	Properties changed	Ref.
Sodium caseinate, sorbitol	*Lactobacillus sakei*	Fresh beef	No alterations in the physicochemical properties with the addition of bacterial cells into the film, significant inhibition of *L. monocytogenes*	[143]
Alginate, Whey Protein Concentrate (WPC), glycerol	*Lactobacillus rhamnosus GG*	Bread	Significant improvement in the viability of *L. rhamnosus GG* by the presence of WPC throughout the air-drying process and at room temperature and reduction of the heat, osmotic, or oxidative stresses that happen in the system	[144]
Alginate/gellan, *N*-acetylcysteine, sunflower oil and/or ascorbic acid and citric acid	*Bifidobacterium lactis* Bb12	Fresh-cut apples and papayas	The Bifidus containing coatings had high WVP than the films, the gellan-based films and coatings revealed better water vapor barrier properties in comparison to the alginate-based coatings, coatings effective in supporting *Bifidobacterium lactis* Bb-12 on fresh-cut apples and papayas	[40]
Sodium alginate, glycerol	*L. plantarum, L. pentosus*	Ham slices	Different organoleptic characteristics with their taste, acidic aroma, while the appearance remained similar	[145]
Alginate, nisin, glycerol	Lactic acid bacteria (LAB)	Smoked salmon	Inhibition of *L. monocytogenes* growth on salmon during refrigerated storage.	[146]

the cells was revealed to be steady till 42 days [123]. In another study, pullulan and starch-based edible films were developed by incorporating probiotic bacteria. Pullulan, starches and their composite (pullulan/starches) films incorporated with *L. reuteri*, *L. rhamnosus* and *L. acidophilus* were kept at 25 and 4 ºC of storage. The maximum viability was detected in pure pullulan-based films at ambient temperature. However, all the films, excluding the starch-based, preserved the cell viability for up to 20 days [124]. In future, it is vital to explore the additional properties and the applications of the polymer materials to successfully safeguard the probiotics incorporated in the edible packaging matrix.

Recent advances in intelligent edible packaging matrices which are used in food industry: Intelligent packaging system represents a new advance in the packaging industry which is found to be capable of detecting, identifying, sensing, recording and reporting related information about the condition, quality and safety of foodstuffs. Intelligent packaging includes food quality indicators such as freshness, gas and pH indicators, data carriers, sensors such as humidity and gas leakage sensors and numerous other biosensors that are used as edible packaging systems. Recent developments in the applications of edible intelligent packaging systems in the food industry are listed in Table-8.

Future trends in edible packaging technology: The new generation of edible biodegradable packaging is under expansion and its industrial applications are still rare. The focus is much needed on the advancement of new technologies and approaches that consent for more effective maintenance of functionality and properties of edible packaging as coatings and films. The new methodologies most commonly include multilayered systems, encapsulation and biocomposites have been developed recently.

These new methodologies consist of micro and nano-encapsulation of active compounds such as alginate, which is more widely used with functional ingredients like enzymes, probiotics, prebiotics and marine oils in edible films or coatings. It may help the encapsulated materials for controlled release of bioactive compounds and their contents under specific conditions, thereby minimizing the moisture loss, improving their stability, protecting from heat, light or other extreme conditions and maintaining the viability.

In contrast, the development of nanolaminate multilayered coatings through the layer-by-layer (LbL) electrodeposition offers promising prospects [125]. This method involves the coating of charged surfaces with interfacial films comprising of multiple nanolayers. These nanolaminate coatings can be synthesized from food hydrocolloids such as polysaccharides,

TABLE-8
RECENT ADVANCES IN INTELLIGENT PACKAGING SYSTEMS AS EDIBLE FILMS AND COATINGS

Matrix composition	Functional property	Application	Ref.
Anthocyanin-rich purple-fleshed sweet potato extract in chitosan matrix	High pH sensing ability, monitoring food spoilage	Monitoring the freshness of fish and pork - pH sensor	[147]
Echium amoenum flower extract in bacterial cellulose	pH-induced colour variations of the films	Monitoring the freshness of shrimp - pH sensor	[148]
Quercetin in carboxymethyl chitosan matrix	Al^{3+} - sensing ability, antioxidant activity	As sensors for Al^{3+} contained food, such as deep-fried dough sticks and steamed buns	[149]
Bacterial nanocellulose, poly (sulfobetaine methacrylate)	Monitoring humidity levels of food	As protonic-conduction humidity sensors to monitor humidity levels in foodstuffs	[150]
Gelatin, gellan gum and red radish anthocyanin	Acting as gas sensors that present noticeable colour changes due to milk and fish spoilage	As for indicators of milk and fish quality - gas sensor	[151]

proteins and lipids and may contain several functional ingredients for example antioxidants, anti-browning, antimicrobial agents, flavourings, enzymes and colourants. Some technical problems have to be faced in coating application on fruits and vegetables and their fresh cuts due to the difficulty in the adhesion of film-forming materials on the fruit surface as a result of its hydrophilic nature. The LbL electrodeposition technique can ultimately resolve this problem, even though it has usually been applied on solid substrates, it can also be applied on hydrogel surfaces [126]. Therefore, the LbL technique possibly can be used to coat such types of highly hydrophilic food structures.

Because of the ability to permit the controlled release of functional ingredients such as additives, antimicrobials, antioxidants, *etc.* the multilayered edible coating matrices have become more beneficial than single-layer coatings in the future. A potential multilayered system is composed of three layers: a biopolymer-based matrix layer; an inner layer to control the percentage of dispersion of the functional constituents by permitting its controlled release and a barrier layer that controls the gas permeability and the migration of the active ingredients to or from the coated food. This property can be applied in the development of edible antimicrobial packaging for the slow diffusion of antimicrobials to the food to preserve antimicrobial properties effectively against pathogenic and spoilage microorganisms.

Conclusion

There is an increasing demand in the food industry as well as by the end consumers in the expansion of new technologies to preserve the foods by extending the shelf-life and ensuring the safety of perishable foods for example fresh and minimally processed fruits, vegetables, fish, meat, cheeses, *etc.* Edible packaging is recognized as a healthy approach to food protection since they are cost-effective, renewable and synthesized naturally. Thus, these coatings and films can be employed as alternatives for synthetic, non-edible packaging for food. Different types of studies have been done in the last few years with advanced technologies regarding the development of edible green packaging to perceive the best outcomes. But to allow their large-scale applications in the food packaging industry, measures have to be taken to solve the drawbacks that occur regarding the technique. Based on some studies, it is indicated that the incorporation of functional ingredients such as antimicrobial agents and antioxidants, especially essential oils and plant extracts into edible films and coatings could impart undesirable changes in sensory parameters in foods. In addition, the incorporation of nutraceuticals into edible packaging may convey bitterness, unpleasant flavour or astringency and certain anti-browning agents can yield an undesirable odour that makes it unpalatable. Therefore, the sensory profiles of edible films and coated food products have to be further evaluated for better consumer acceptance. Further, researches need to focus on commercial-scale applications of edible packaging for foods. A new generation of edible packaging for foods can be further developed by the incorporation and/or control of the active compounds release by employing nanotechnological solutions such as nanolaminate layer-bilayer multilayered systems and nanoencapsulation to improve the barrier properties, increase stability and viability. The most recent updated advancements of using edible packaging as a novel, ecofriendly alternative to commercial, synthetic non-edible plastics in food packaging applications reflect their high capability of being initiated in the industry as well in the market in succeeding years.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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