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Abstract

The growing general consciousness in relation to gluten intolerance has driven the food industry to find alternatives to provide adequate products to the consumers with disorders related to gluten intake. The present chapter deals with the descriptions, characterisation and main applications of eco-friendly and edible films, coatings and toppings used in the production of bakery products. Particular requirements that must be fulfilled to be applied to gluten free bakery foods are remarked. A description and guidelines of the different components, preparation and application techniques, as well as, the methodology to determine films and coating properties, are summarised. In addition, the main applications of edible matrices to improve the global quality and extend the shelf-life of bakery products are listed. It was also highlighted the overall importance of edible matrices to constitute systems that allow to protect, retain or control the release of different functional additives. Special attention was paid to the potential of edible films and coating as vehicles to incorporate probiotics, bioactive compounds and/or nutrients into the formulation of gluten free baked products. Hence, this chapter pretends to highlight the relevance of edible coverings as a useful and feasible strategy for providing celiac consumers with safe, attractive and nutritious foods products.

Keywords (separated by “ - ”)

Edible coverings components - Toppings constitution - Physical characterisation - Functional bakery products - Active films and coatings

Chapter 7
Gluten Free Edible Films, Coatings and Toppings

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Abbreviations

AFM	Atomic force microscopy
ASTM	American society for testing materials
Tg	Glass transition temperature
GF	Gluten free
HPMC	Hidroxyporpyl methylcellulose
LDPE	Low density polyethylene
MC	Methylcellulose
OPP	Oriented polypropylene
SEM	Scanning electron microscopy

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a_w	Water activity
WVP	Water vapour permeability

7.1 Introduction

The gluten intolerances have determined diet changes based on the elimination of ingredients that contain prolamins and glutenin from wheat, rye and barley being replaced, in part, for alternative grains and tubers that do not induce the disease, for instance, rice, corn, sorghum, and millet (Lebwohl and Green 2021). This has led to an important challenge for the food industry due to the need of developing formulation strategies, generally known as "gluten free" (GF) ones, that include the use of suitable additives linked to this dietary modification, while helping to produce safety and organoleptically adequate food products (Zoumpopoulou and Tsakalidou 2019). According to the Food and Drug Administration (U.S.A.), the GF food is defined as the food that does not contain gluten, or its presence should be lower than 20 ppm (McCabe 2010).

Bread and sweet baked goods (cakes, biscuits, doughnuts, etc.) are an essential constituent of the human daily diet, representing the most important basic food worldwide (Nils-Gerrit Wunsch 2020; Xu et al. 2020). There is a wide assortment of such products and, a possible classification is the one proposed by Smith et al. (2004) who grouped them as follow: unsweetened (bread, rolls, buns, crumpets, muffins, and bagels), sweet (pancakes, doughnuts, waffles, and cookies) and filled (fruit and meat pies, sausage rolls, pastries, sandwiches, cream cakes, pizza, and quiche) goods. In their formulation, these products include complex carbohydrates (mainly wheat flour), proteins, lipids, vitamins, and minerals (Soukoulis et al. 2014).

Another classification proposed is based on the water activity (a_w), one of the most important product properties affecting the physical and microbial deterioration of bakery products. Smith and Simpson (1995) classified bakery products as follow: (a) low moisture bakery products (cookies and crackers, $a_w < 0.6$) in which microbiological spoilage is not a problem, (b) intermediate moisture products (chocolate coated, doughnuts, Danish pastries, cream-filled cake, soft cookies, a_w 0.6–0.85) where osmophilic yeasts and moulds are the predominant spoilage microorganisms, and (c) high moisture products (bread, pita bread, fruit pies, carrot cake, cheesecake, pizza crust, pizza, $a_w > 0.85$ and generally 0.94–0.99), where almost all bacteria, yeasts, and moulds are capable of growth (Smith et al. 2004).

When no preservative additives are added, bread and bakery products are characterised by their limited shelf-life reaching a maximum of 3–5 days at room temperature. After this time, physical, chemical and microbiological changes are produced, resulting in the loss of freshness, texture, taste and microbial spoilage (growth of bacteria, yeast and mould) causing consumer's rejection (Melini and Melini 2018). Those alterations can cause not only economic losses, but also threaten human health. Therefore, to extend bread and bakery products shelf-life and to assure their quality and safety properties, preservation techniques such as the use of preservatives or adequate packaging materials and the application of innovative processing technologies are proposed (Mitelut et al. 2021; Qian et al. 2021).

Over time, one of the most conventional technique applied to extended freshness quality was the use of chemical additives as was previously detailed in Chap. 4. The bakery industry is looking for novel alternatives including the use of antioxidant and antimicrobial compounds obtained from natural sources, new packaging technologies, application of functional coatings, etc. (Klinmalai et al. 2021; Silva et al. 2021; Nallan Chakravartula et al. 2019a).

Traditionally, to select a suitable packaging material for bakery products, the most important properties usually sought are gases and water vapour barrier, UV barrier, thermal stability, mechanical resistance (Roy and Rhim 2020). The most used packaging materials to preserve bread are different types of paper, such as waxed paper or the glazed imitation parchment which is strong and has grease resistance. It is usually impregnated on both sides with paraffin wax containing low density polyethylene (LDPE) and other additives (Martins et al. 2021). One alternative is LDPE bags with a strip of adhesive tape at the end to be twisted and sealed. Cakes and pastry products, which are more susceptible to crushing damage, are usually packed in grease-resistant paperboard bags with transparent cellophane windows and wrap, such as cling film, plastic nests or aluminium foil base plates and double plastic film layers. For long shelf-life products (biscuits and other), cellulose films coated with LDPE are generally used (De Pilli 2020; Galić et al. 2009) or other multi-layered films such as aluminium-coated LDPE, oriented polypropylene (OPP) or acrylic-coated OPP films which represent more effective barriers to oxygen and water vapour. In the case of fresh baked stuff immediately consumed, it is commonly packaged in bags made of polyolefin film, such as LDPE or polypropylene bags, normally micro-perforated to allow moisture to escape and avoid leathery consistency of the crust (Pasqualone 2019).

Regarding packaging methods, the application of new technologies such as vacuum packaging, nitrogen flushing, modified atmosphere, functional or active packaging (with antimicrobial activity) reduce the growth of spoilage microorganisms, extending bakery products shelf-life (Qian et al. 2021).

It is important to highlight that the plastic derived from fossil hydrocarbons comprise 46% of global plastic waste generation, producing a huge impact to the environment, which often end up in landfill sites or oceans, causing a significant pollution due to the poor infrastructure, the lack of recycling options and to the long periods of time required for their degradation (Tiseo 2021; Geyer et al. 2017). Thus, there is a wide interest in the development of new materials for substituting plastic packaging by using renewable resources to reduce polluting residues.

In this framework, biodegradable packaging has emerged as an innovative and promising solution since they decompose after fulfilling their purpose (Chiralt et al. 2020; Tapia-Blácido et al. 2020). New biodegradable materials can be classified in chemically synthesised polymers made from natural or petroleum-based molecules (polylactic acid, polycaprolactone, polyvinyl alcohol, polyglycolic acid, polybutylene succinate, polybutylene adipate-co-terephthalate); directly extracted from biomass (biopolymers such as cellulose, starches, chitosan, alginate, gelatine, collagen, etc.) and biosynthesized via microbial fermentation (polyhydroxyalkanoates, bacterial cellulose) (Zhang et al. 2022; Kamarudin et al. 2022; Birania et al. 2022). These have been used to develop new eco-friendly and active systems that could be applied to protect or improve quality of GF bakery products. In the following sections of this chapter, a special description of biodegradable and edible matrices is performed.

7.2 Edible Films, Coatings and Toppings

7.2.1 Edible Films and Coatings

The named edible films can be defined as standalone materials disposed as thin layers based on eatable components (biopolymers, food additives, etc.) and are generally used in the production of wraps, pouches, bags, capsules and casings. On the contrary, coatings involve slurries that are directly applied (by deposition, adhesion and drying) on the food surface and are considered as an integral part of the food product. They are designed not to be removed from the food item. Usually, they can be classified according to their formulation or the application method used, as will be described in the methodology section. To obtain edible packaging the following main technique stages must be performed: achieving the solubilisation of the biopolymer in a suitable solvent to obtain the slurry (for films and coatings) or mixing solid materials if it is used a thermomechanical process (without solvent addition, for films), solvent evaporation when corresponding and film constitution and stabilisation. There are no differences in the material composition between coatings and films but they are mainly different in relation to their thickness (Aguirre-Joya et al. 2018).

Edible active packaging is an innovative solution due to its capability to carry preservatives compounds, which reduce the microorganism's growth and assure the safety and quality of foods extending their shelf-life (Jafarzadeh et al. 2020; Fang et al. 2017). Certain additives can be incorporated into the edible packaging formulation such as antimicrobials and antioxidants compounds (Qian et al. 2021; Dobrucka and Cierpiszewski 2014).

There are different methods to incorporate those compounds (Qian et al. 2021):

(a) Direct incorporation of preservatives (thermally stable) into the packaging materials produced by solvent casting or extrusion technology (co-extrusion, extrusion or injection moulding);
(b) Surface coating of packaging material with a film containing antimicrobial agents (essential oils derived from plants, such as cinnamon, clove, oregano, thyme, and lemon) entering the headspace through evaporation or migration to the food surface through diffusion (Mani-Lopez et al. 2018; Fang et al. 2017). This method illustrates an additional use of films;

(c) Sachet/pad of antimicrobial packaging (non-volatile or volatile) are designed to hold by adsorbing or embedding the antimicrobial agents to be released inside the package continuously (Ju et al. 2019; Otoni et al. 2016). This type of packaging presents some limitations such as, the risk of accidental ingestion and additional operational steps to place them in each package;

(d) Stimuli-responsive antimicrobial packaging, in which responsive nano-carriers can encapsulate active compounds materials and release them on demand when an external stimulus (light, temperature and pressure) is applied (Qian et al. 2021).

Regarding the materials, as structural material or film matrix, biopolymers are generally used. These might be: (a) hydrocolloids that includes proteins such as collagen, gelatine, mung bean protein, corn zein, whey protein, soy protein, casein and others (Chen et al. 2019); and polysaccharides such as starch, cellulose and its derivatives, pectin, chitosan, alginate, carrageenan, pullulan and gellan gum (Kouhi et al. 2020); (b) lipid-based materials (bee wax, paraffin wax, carnauba wax, polyethylene wax, candelilla wax, rice bran wax, ouricury wax and jojoba oil); and (c) blend of hydrocolloids and lipids (Jeya Jeevahan et al. 2020; Zhong et al. 2019).

Moreover, they have to be aligned with the consciousness growth on celiac disease and gluten intolerance, which represents one-third of the global food intolerance market, added to consumer's choice to follow a GF diet that has had an important impact in the growth of GF products in the last 10 years (Juhász et al. 2020). In this context, the use of ingredients that provide safety characteristics and additionally have favourable nutritional and mechanical profiles to be used as edible packaging materials has become a focus of interest (Vilpoux et al. 2019).

Other hydrocolloids are the most crucial ingredients in edible packaging for GF baking products such as hydroxypropyl methylcellulose (HPMC) and carboxymethylcellulose (CMC), present good barrier properties against oxygen and lipids in film formulation (Roman et al. 2018; Anton and Artfield 2008). Likewise, β-glucan, pectin, carrageenan, xanthan gum, guar gum, locust bean gum, tara gum or agarose are applied in commercially available GF products (Vidaurre Ruiz et al. 2019). CMC, chitosan, ε-poly-ʟ-lysine are natural polymers that present desirable film-forming properties and also antimicrobial activity (Fang et al. 2017).

Regarding starch sources, wheat, rye, and barley are common cereals containing gluten. Besides, contamination of oats with wheat, rye or barley can occur during grain harvesting, transport, storage and processing (Xu et al. 2020). Previous research has been extensively focused on GF edible packaging made from various natural GF starches such as potato, sweet potato, cassava, rice, sorghum. Figure 7.1 summarises main materials used to formulate GF edible films and coatings.

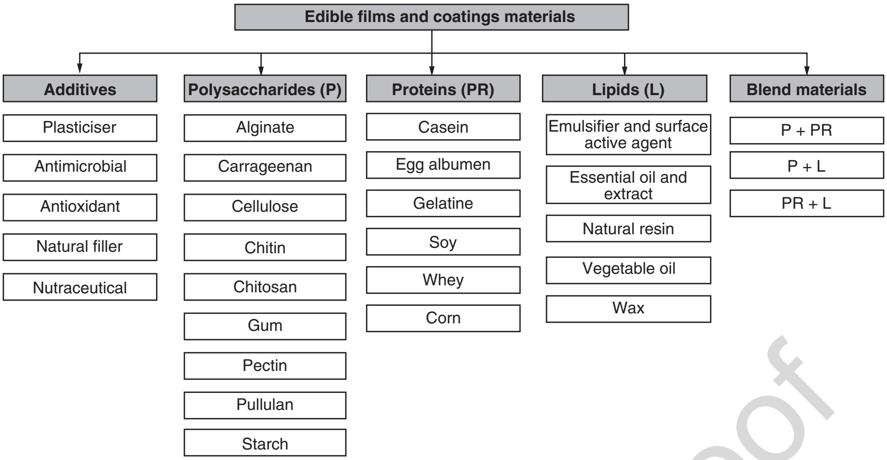

Fig. 7.1 Main materials used to formulate GF edible films and coatings

7.2.2 *Toppings*

To achieve a more attractive appearance and therefore a greater degree of acceptance by consumers, toppings are incorporated into bakery products. They create a decorative quality and provide additional flavour with the addition of small particles (chunky, crisp or chewy bits) contributing different textures, flavours and colours, widening the range of products considerably. Toppings are applied mainly for aesthetic and decorative reasons, however, in some cases they positively contribute by providing also desired technological effects, such as to promote the regulation of water activity at the surface of the product or reduce the risk of microbial growth. Additionally, the access of oxygen can be minimised, preventing the exposure to light and protecting the product mechanically. By combining these positive effects, it is possible to extend the shelf-life of bakery products (Tiefenbacher 2017).

Frequently, toppings consist of dry ingredients, such as seeds, grains, chopped nuts, cereal crisps, fruit pieces (candied or dried), chocolate chips or sprinkles, cocoa (nibs roasted and powder), cookie crumbles, puffed marshmallow, jelly bits, flavoured bits, cheese, herbs, seasonings (spices), toffee (milk caramel) or fudge bits, sugar (powder or crystals), or salt that are sprinkled superficially on the dough or in the final product. When those ingredients in small discrete pieces are added into filling creams, chocolate enrobing or bakery products are called inclusions (Tiefenbacher 2017).

Moreover, wet toppings or wet ingredients can be applied on bakery products by frosting (thick and opaque mixture) covering the surface and sometimes filling the inside of cakes. Some examples are icing, mixture of confectioners powdered sugar and liquid, thin enough to be brushed on with a pastry brush or spread on pastries, rolls, and simple cakes; glaze or enrobing. Other examples are a mixture of sugar and liquid thin enough to be poured – about the consistency of thin corn syrup to coat fruit cakes, cupcakes and pieces of cake; and fillings like a thick mixture which is used between the layers of cake. It may be some of the frosting to which nuts, marshmallows or fruits are added. Whipped cream and custard mixtures are sometimes used for fillings (Tiefenbacher 2017) and natural or untreated cocoa is often used in frostings, icings, and fudge (Ortiz 2016).

In bakery products like muffins, toppings can be as simple as a cinnamon/sugar blend or as complex as a nut streusel. Some toppings are also materials meant to ‘sink in’ to the muffin creating a ‘filling’ such as the addition of a sweet cream cheese mixture, creating changes in texture and flavour as the consumer eats the product. In bagels, toppings (seeds, finely chopped onion, or salt) are often coated on the top after boiling and before baking (Ortiz 2016). Table 7.1 shows different sources of ingredients used for bakery toppings.

Table 7.1 Raw and partially processed gluten and GF sources used for bakery toppings

Source	GF food matrix	May contain gluten trace	Gluten
Grains and alternatives	Amaranth, buckwheat, chestnut, corn (maize), millet, cornmeal, quinoa, rice, sago, sorghum, soya, tapioca, teff, uncontaminated oats		Barley, bulgur wheat, couscous, dinkel wheat, durum wheat, einkorn wheat, emmer wheat, Kamut, rye, semolina, spelt, triticale, barley, oats
Milk products, cheese and eggs	Cheese, eggs, and milk (liquid and dried) cream (single, double, whipping, clotted, soured), buttermilk, plain yoghourt	Some soft and spreadable cheeses, coffee and tea whiteners, fruit and flavoured yoghurts, and soya desserts	Yoghourt, or muesli with whole grains
Fruit, vegetables, nuts, seeds, and pulses	Fresh, frozen, canned, dried, baked, and boiled fruit and vegetables. Plain nuts, seeds, and pulses	Fruit pie fillings, processed vegetable products, deep-fried, microwave, and frozen chips, instant mash, potato waffles, roast potatoes. Roasted nuts and pulses in flavoured sauces (baked beans)	Fruit in batter and bread crumbs
Home baking	Arrowroot, artificial sweeteners, corn starch, cream of tartar, food colouring, gelatine, icing sugar, potato starch, ground almonds	Baking powder, cake decoration, marzipan, ready-to-use icing	Batter mixes, bread crumbs, stuffing mix
Confectionary, desserts, and savoury snacks	GF jelly, licorice root, seaside rock, homemade popcorn, plain rice cakes, and crackers	Chocolate, ice cream mousses, sweets, tapioca pudding. Flavoured popcorn, potato and vegetable crisps, flavoured rice cakes, and rice crackers	Made from wheat, rye, and barley, pretzels, wafers, licorice sweets, pudding made using semolina or wheat flour

Adapted from Jones et al. (2016)

7.3 Preparation and Characterization of Edible Films, Coatings and Toppings

Several technologies can be used to produce and study edible films, coatings and toppings. Differences arise basically from food type and form of application on the final product, the materials composition and properties requirements. For instance, edible coatings are usually directly applied on the food product surface, while edible film is separately produced and later used as packaging material. Various biopolymers such as polysaccharides, proteins, lipids and their composites are used in films and coatings formulations, most of which are GF, thus a wide spectrum of properties and processing conditions are possible and need to be studied and optimised regarding the final product requirements. Besides, aiming to further extend the food shelf-life span, many active films and coatings have been developed, most of which contain essential oils (EOs) and other antioxidant or flavonoids rich compounds. These are usually volatile or thermosensitive compounds which limit the film or coating preparation and application technologies.

7.3.1 Processing Technologies

Edible films can be manufactured by two techniques: a *wet route* based on a biopolymer solution (usually water based) with further solvent evaporation, known as *casting;* and a *dry route* in which polymers are processed in low moisture conditions with the presence of plasticisers and other additives (e.g., compression moulding or extrusion). The first is a batch process with some limitations, such as restricted product size and yield, long production times, high energy demand (for solvent evaporation) and large volumes of solvent (since solids do not exceed 10–12% of the suspension total mass). Therefore, it is mainly used at a laboratory scale, still extensively studied for surface coating characterisations. Besides, semi-continuous *tape-casting* and *spread-coating* techniques can also be used for large-scale manufacture of biodegradable and edible films (Oliveira de Moraes et al. 2013). In both techniques the film forming solution (or suspension) is spread over the laminated material to be coated (paper for example) or directly on a non-adherent carrier-tape. The film thickness is adjusted with micrometric screws that regulate the gap left by the spreading blade and depends strongly on the solution's rheological behaviour (Ortega et al. 2021). The suspension is later dried by heat conduction, circulation of hot air (heat convection) or infrared heating, resulting in a bi-layer material (spread-coating) or film that can be easily removed from the tape-carrier surface. Later on, and depending on the film characteristics, it can be rolled, cut, drilled, stamped or laminated. Various GF edible films obtained by casting have been studied as biodegradable or edible packaging for foods based on starches (Bertuzzi et al. 2007; Flores et al. 2007; Müller et al. 2008; Oliveira de Moraes et al. 2013; Pérez-Vergara et al. 2020; Mantovan et al. 2018; López and García 2012; Versino et al. 2016), pectins (Troung and Kobayashi 2020; Nallan Chakravartula et al. 2019b; Fishman et al. 2000; Sucheta et al. 2019; Gouveia et al. 2019), gelatine (Fakhouri et al. 2015; Musso et al. 2017; Wang et al. 2021), chitosan and other marine derived hydrocolloids (Senturk Parreidt et al. 2018a, b; López et al. 2015; Pranoto et al. 2005; Tan et al. 2020; Fu et al. 2021; Morales-Jiménez et al. 2020), soy, whey and pea proteins (Seung and Rhee 2004; Denavi et al. 2009; Nallan Chakravartula et al. 2019b; Seydim et al. 2020; Huntrakul et al. 2020; Sun et al. 2013), among others. Drying conditions are strongly dependent on the biopolymer and solvent used, temperature typically ranges from room temperature to 60 °C with drying times of 5 to over 48 h. In casting method films thickness can be adjusted by controlling the ratio of film suspension weight to plate area. Drying conditions (rate and temperature) determine film characteristics (e.g., water content, crystallinity, etc.), affecting its microstructure and properties (Bader and Göritz 1994)

Larger scale production technologies are needed to produce cost-effective, bio-based edible materials as food packaging. Thus, existing technology for synthetic materials are also used as continuous technologies like extrusion followed by blown, injection or thermo-compression (Mohammadi Nafchi et al. 2013; Flores et al. 2010; Garrido et al. 2016; Huntrakul et al. 2020; Fakhouri et al. 2013). Melt processing requires high temperatures and shear to disrupt the biopolymers' original structure, plasticising it. However, additives, such as plasticisers and antioxidants, are needed to thermally plasticise the polymer mix avoiding its degradation (Ortega et al. 2021).

Thermoplastic starch (TPS) based films are obtained by melt-mixing, though it is highly sensitive to moisture and present stickiness during processing (López et al. 2013b). Therefore, blending the starch with other polymers improves film formability, and mechanical, barrier and thermal properties as has been extensively reported in literature (Dang and Yoksan 2015; Pelissari et al. 2012; Fakhouri et al. 2013; Huntrakul et al. 2020; Ochoa-Yepes et al. 2019; Jebalia et al. 2019; Ferreira et al. 2021; Fishman et al. 2000; Flores et al. 2010). Extrusion can be single, twin or multiple screwed co-rotating or counter rotating (i.e., screws rotate in the same or opposite directions respect to the feed and product flow) or a mixture of both in the case of a multiple screw extruder. Temperature profiles through the extruder are important parameters for polymer processing that facilitate commercial processability and condition the materials properties.

The selected film processing technology influences the film formation mechanism and therefore the resulting physical properties of the material. Casting creates films stabilised largely by non-covalent interactions (hydrogen bonds, hydrophobic and electrostatic interactions) while extrusion and compression moulding may induce covalent interactions among the matrix compounds. Some investigation comparing these technologies indicate that extruded materials result in greater toughness and stiffness while casting films are more flexible, especially when cross linkage was evidenced in thermoformed or extruded materials (Ciannamea et al. 2014; Versino et al. 2016; Ochoa-Yepes et al. 2019).

Active packaging technologies offer new or extra functions such as gases scavengers (O_2, CO_2, and ethylene), moisture regulation, flavours emission control and preservation, microorganism growth prevention, among others, that are aimed to extend the shelf-life of foods maintaining their nutritional quality and safety

(Kechichian et al. 2010; Jamróz and Pavel 2020; Remya et al. 2017). Active films are usually prepared with the same methods previously described, though alternatives for protection and migration control are usually needed when EOs are used. Encapsulation and electrospinning have been reported as successful methods to preserve and modulate the EOs antimicrobial or antioxidant properties (Scaffaro et al. 2020; Varghese et al. 2020; Sharifi and Pirsa 2021; Atarés and Chiralt 2016). Moreover, Oriani et al. (2014) stated that a maximum of 0.1% of EOs into an edible coating minimises their sensory impact; encapsulation can also be used in this regard.

Edible coating can be applied on a food product by four different techniques: *dipping, spraying, fluidized-bed,* and *panning* (Senturk Parreidt et al. 2018a, b; Suhag et al. 2020). Its efficiency is strongly dependent on the selected application procedure, regarding the nature of food that should be coated, such as shape and size, their surface characteristics and the desired coating thickness and the coating material properties such as surface tension, density, and viscosity (Andrade et al. 2012). Dipping is the most widely used method to apply edible coatings on fresh products, particularly in ready to eat fruits and vegetables. In general, they are submerged for 5–30 s in the formulation of edible coatings which commonly can include antimicrobials and/or antioxidant to extend product's shelf-life (Suhag et al. 2020; Guerreiro et al. 2015; Senturk Parreidt et al. 2018a, b). It is a simple and low-cost technique commonly used at laboratory scale. The process consists of three steps: immersion, deposition, and evaporation of solvents (Andrade et al. 2012; Costa et al. 2014). Adhesion of the coating solution relies on the interaction with the food surface. For instance, smooth and uniform adhesion on hydrophobic rough surfaces can be very difficult due to the low surface free energy (Senturk Parreidt et al. 2018a, b). Meanwhile, when the coating affinity for the product surface is high, the time required will be minimal, allowing the coating solution to be applied spontaneously (Park and Seo 2011). Multilayer or layer-by-layer coating techniques are often needed in fresh cut products to achieve good adhesion on the highly hydrophilic surface. In this regard, Guerreiro et al. (2015) applied an edible coating to raspberries by first immersion into alginate or pectin coating solution followed by the immersion in a calcium chloride solution, allowing to form the typical egg-box gel due to the chemical gelation of the hydrocolloid in presence of a bivalent cation salt.

On the other hand, the spraying method is frequently used for industrial applications, in this technique the coating solution is distributed through the formation of droplets over the targeted food surface area with the help of nozzles (Suhag et al. 2020). One of the advantages of the spraying technique is that it needs less amount of coating material to effectively coat the surface product due to the high spraying pressure used (60–80 psi) (Andrade et al. 2012). Additionally, the thickness control as well as the possibility of multilayer applications are also valued characteristics. Spray-flow characteristics are dependent on liquid properties (density, viscosity and surface tension), operating conditions (mainly flow rate and air pressure), and system conditions (nozzle design, spray angle, etc.). Three types of spraying techniques have been used: (i) air spray atomization, where air is used for fine spraying of the droplet on food products; it is a cost effective method used on food products (Valdés et al. 2017), (ii) air assisted airless atomization, when high-viscosity and high-solids coatings formulations are used (Peretto et al. 2017), and (iii) pressure atomization, in this technique, the edible coating is applied to food products by passing it through small size nozzles (Andrade et al. 2012).

Likewise, edible coatings can serve as adhesive for decorative toppings, which are commonly included in bakery products (typically between 12% and 22% volume percentage of the total product) to enhance their attractive sensory characteristics (Tiefenbacher 2017). In this sense, small particulate inclusions or decorative toppings of different texture, flavour and colour can be used. Examples of currently used toppings in bakery products are chopped nuts, cereal crisps, candied fruit or toffee pieces, chocolate chips, cookie crumbles, flavoured bits, sugar or chocolate sprinkles, coarse sugar or spices. These are processed by conventional food processing technologies, such as air drying, extrusion cooking, melt mixing, etc. and are usually GF if cleaning protocols are carefully managed.

Recently, 3D printing of edible inks and pastes have been studied and commercialised, especially as food toppings. This technology expands the food processing alternatives for customizable nutrient content food products (Dankar et al. 2018). Current 3D food printing techniques include paste extrusion, ink-jet printing, powder binding deposition, sheet lamination, melt extrusion of chocolate, and bioprinting (Rowat et al. 2021).

7.3.2 Characterisation

The performance of edible films and coatings in extending food products shelf-life depends on the materials light, water vapour and gas permeability and their mechanical properties to resist transport and different ambient conditions. Coating integrity is a critical factor that depends on matrix flexibility, surface tension and adhesion to the food product. Besides, rheological characteristics and surface adherence are of particular importance for edible coating formulations, due to their direct impact on surface covering and durability. Similarly, controlled or slow-release kinetics determine its performance as active material and therefore its effectiveness on the product preservation. Finally, such properties need to be preserved by the film or coating until the food that it wraps is consumed or, in the worst case, disposed of. Consequently, all properties should be evaluated through time, ideally simulating the storage conditions and average time until consumption of the packed or coated food product.

7.3.2.1 Rheological Behaviour and Surface Properties

Rheological properties of film suspension should be tailored to fit the coating process: spraying requires low viscosity while higher viscosity is needed for immersion coating. The thin film formed on food surfaces depends on the viscosity of the coating solutions and can be well controlled with a specific spray-gun application

(Andrade et al. 2012; Suhag et al. 2020). This technology offers consistent coating with uniform thickness, and the possibility for multilayer applications (Martín-Belloso et al. 2009; Ustunol 2009). The highly viscous solution cannot be sprayed very easily on the food products so that only dipping methods can be adapted which results in the higher thickness of the coating material on the surface of food products (Andrade et al. 2012).

Likewise, considering the scale-up of the coating or film production the rheological behaviour of filmogenic solutions or suspensions is critical and conditions the processing operations involved, such as the pumping machine capacity. In general, starch-based filmogenic suspensions, which are widely used in coating formulations, exhibit a pseudoplastic behaviour while other formulations based on polysaccharides such as cellulose derivatives (like methylcellulose (MC) or HPMC) presented a Newtonian behaviour at low concentrations (1%).

On the other hand, coating formulation and mainly, its surface tension as well as food product characteristics determine the adhesion to food substrate and successful coating application. Products with smooth and soft surfaces (such as some vegetables like tomato) require formulations with low surface tensions to ensure coating adherence and uniformity. For products with irregular and rough surfaces (such as strawberries) the formulation must include plasticisers to prevent the appearance of cracks or pores in the coating. An alternative to enhance coating adhesion is the addition of surfactants and lipids to filmogenic suspensions, reducing their surface tension. The more similar the surface tensions of the product surface and that of the coating formulation, the greater the compatibility and the better the adhesion of the coating. Coating compatibility also is related to the hydrophilic-hydrophobic characteristic of both the surface and the formulation, which could be evaluated through contact angle measurements (Ramírez et al. 2012; Rossi et al. 2019).

Film or coating superficial appearance depends on their formulation, since matrices without plasticisers are brittle and rigid due to the strong interactions between the polymer chains that can also lead to aggregate formation. Besides, these structures are incompatible with irregular product surfaces leading to cracks and pores and conditioning coating integrity. The presence of these defects also limits barrier and mechanical properties of films and coatings. Plasticiser addition in the formulations can solve this problem by improving the coating flexibility (García et al. 1998; López et al. 2010). Likewise, the plasticiser/polymer ratio should be optimised since high plasticiser concentrations reduce barrier properties and may cause segregation from the matrix. In starch-based formulations glycerol or sorbitol are commonly used as plasticisers in concentrations between 5 and 50 g/L, depending on starch concentration (García et al. 2009; Versino et al. 2016).

7.3.2.2 Mechanical Properties

Uniaxial tensile tests are usually performed to assess the film's mechanical resistance. From these tests, strain-stress curves are obtained and the Elastic Young Modulus, maximum tensile strength and elongation at break are assessed. The mechanical properties depend on additives-matrix interactions that can also be strongly affected by physical, chemical, and environmental conditions, which influence the material stability and flexibility. Plasticisers are often needed to enhance the materials flexibility, especially in starch-based films and coatings (Versino et al. 2016). The addition of lipids, including essential oils has also been reported to increase extensibility of biopolymers-based materials (Bof et al. 2021; García et al. 2001; Jamróz and Pavel 2020).

On the other hand, dynamic mechanical analysis is a useful tool to study relaxation processes associated with glass transition temperatures (Tg). The Tg corresponds to the temperature at which tanδ and E” (loss moduli) curves presented a maximum peak while E’ (storage moduli) curve shows an abrupt fall. It has been widely used especially in starch-based formulations. The knowledge of the Tg is crucial since it is strongly related to mechanical film properties and also, modifications on both film formulations and storage conditioning may affect Tg and consequently the mechanical resistance and flexibility of developed films. In this sense, the inclusion of plasticisers decreases the intermolecular forces between polymer chains and consequently reduces Tg values. Thus, being water the most ubiquitous plasticiser of hydrophilic films and coatings, film water content and relative humidity of storage should be carefully controlled and monitored.

7.3.2.3 Barrier Properties

Water and gas barrier properties are key for food products preservation. Gas permeability is usually tested on films or the coating standing by its own (also as a film). Water vapour permeability (WVP) is often determined gravimetrically according to American Society for Testing Materials (ASTM) standard test method, ASTM E96/E96M or a modification of this norm, thus various relative humidity conditions have been reported (Huntrakul et al. 2020; Nallan Chakravartula et al. 2019b; Musso et al. 2017; Ochoa-Yepes et al. 2019; Fakhouri et al. 2015). The WVP indicates the ability of the film or coating to protect the food from moisture migration from or towards the product. For instance, to prevent pastry from drying which would not be desirable for texture acceptance by the costumer or to prevent an increase in moisture content and water activity, which can promote mould growth and a faster degradation of the product. Unplasticised films often yield significantly higher WVP values than plasticised ones, due to the presence of pores and cracks (Versino et al. 2016). Even though plasticisers used in edible films and coatings are generally hydrophilic, its inclusion generates structural modifications on the biopolymer network leading to a less ordered and compact structure. In general, starch-based films exhibit lower WVP values compared to both protein films and other polysaccharide-based films (García et al. 2001, 2004; Versino and García 2014; Rivero et al. 2010; Tavassoli-Kafrani et al. 2016).

Considering that hydrocolloid-based films are very sensitive to relative humidity, physicochemical characterisation generally includes water sorption isotherms determination, useful for the estimation of film stability under different ambient conditions. In general, sorption isotherms are obtained, being experimental data satisfactorily fitted by GAB model, estimating the monolayer water content values (Mali et al. 2002; Müller et al. 2009).

Regarding film gas permeability most methods use the same principle: a measurement of the gas transmission rate through an edible film located between two compartments. One side of the film is exposed to the gas being studied, and a detector is placed in the other compartment, which is initially free of the permeated compound (Sánchez-Tamayo et al. 2020). These methods were developed for synthetic materials, described in the ASTM procedures, and adapted to edible films and coatings (ASTM D3985, F1927). The manometric and the volumetric methods measure the difference in absolute pressure, and the continuous-flow or isostatic method uses a stream flux of the gas to be measured on one side of the film and a nitrogen stream on the other side to carry the gas to the analyser. Coulometric sensors, infrared sensors, or gas chromatography may be used for gas concentrations analysis. In the case of O_2 permeability the use of specific equipment, the Mocon Oxtran 2/21, is widely used due to its precision and simplicity. Although for CO_2, N_2 and ethylene the determination requires the use of an especially designed cell and in general chromatography measurements. It is well known that polysaccharides films such as starch-based ones exhibit a highly selective gas permeability ratio (CO_2/O_2) compared with conventional synthetic materials. The modified atmosphere created by the coating generates a physical capture of CO_2 inside the fruit or vegetable and partial sealing of the pores, reducing the gas exchange and gas transfer rates; and this is monitored through respiration activity measurements. This selective gas permeability can be attributed to a higher solubility of CO_2 than O_2 in the film matrix. Development of composite edible films and coatings with selective gas permeability could be promising for controlling respiratory exchange and improving the conservation of food products.

7.3.2.4 Microstructure

The materials microstructure is generally studied by microscopy techniques, mainly scanning electron microscopy (SEM) or atomic force microscopy (AFM). Compact and homogeneous matrix of films is an indicator of structural integrity and, consequently, good mechanical properties are expected. To evaluate this, SEM observations of both the surface and the cross-sections are carried out. Figure 7.2 shows the microstructure of an edible coating based on HPMC applied on pumping vegetable tissue.

Topography and roughness of starch films surface can be evaluated by AFM. In the case of nanocomposite films transmission electron microscopy is also conducted to evaluate the nanometric size particles included in the matrices.

Interactions among film-formulation components as well as their compatibility are commonly studied by Fourier transform infrared spectroscopy, being this technique combined with chemometric analysis. In order to evaluate the crystallinity degree of edible films and coatings X-ray diffraction is commonly performed. Film crystallinity depends on the biopolymer source and plasticisers, film drying

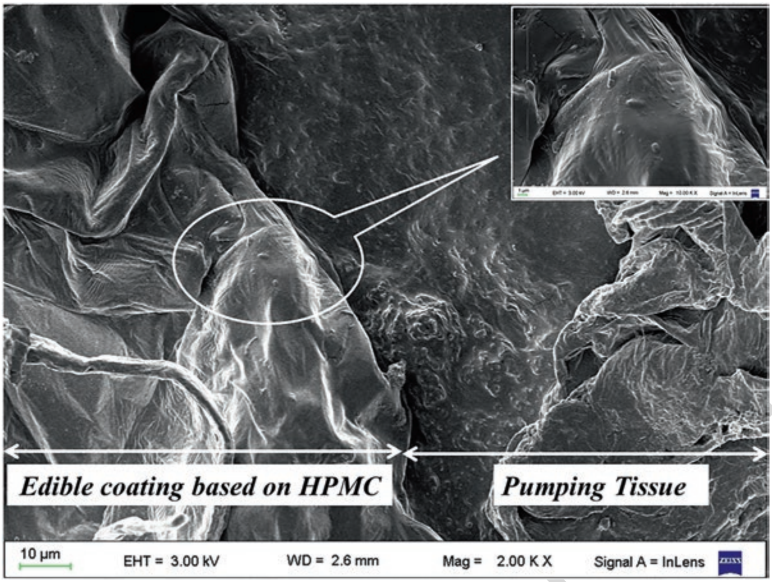

Fig. 7.2 Microstructure of an edible coating based on HPMC supporting *L. casei* cells and applied on pumping vegetable tissue

conditions and their final moisture content (García et al. 2009). Evolution of film matrix crystalline structure during storage can also be evaluated by differential scanning calorimetry, which allows to determine the Tg, being in this case the modulated technique more appropriate since it discriminates between the total heat flux, and the reversible and non-reversible contribution.

7.3.3 Characterisation After Application on Food or Simulated Food Systems

In the case of edible coatings and toppings a complete sensorial analysis is mandatory, showing that the coatings did not influence consumer acceptance, especially when taste is evaluated. In general, sensory panels are performed with both trained and untrained panellists on the basis of a hedonic scale. The selection of panellists includes men and women covering a wide age range to simulate the spectrum of potential consumers of the product being evaluated. In this sense, adhesion properties evaluation should be taken into account, especially for products destined for distant markets or long term storage, since it conditions the coatings' performance (Ncama et al. 2018).

Likewise, the microbiological tests should be conducted to assure the product safety. In this sense, the absence of microorganisms that cause foodborne illness as well as the counts of aerobic mesophilic and psychrophilic bacteria and mould and yeasts are commonly evaluated following standard procedures. This is of particular interest when active films and coatings are applied to extend food shelf-life. In this sense, López et al. (2013a, b) developed films based on blends of native and acetylated corn starches containing glycerol as plasticiser, potassium sorbate and citric acid as antimicrobial agents. The developed active starch films were able to inhibit *Candida spp., Penicillium spp., S. aureus and Salmonella spp.* growth, which are responsible for some foodborne diseases. These active films were effective to extend cheese shelf-life from 14 to 17 days at 4 °C. Besides, sorbate controlled release from the polymeric matrix was studied and diffusion coefficients in aqueous and semisolid media were also determined (López et al. 2013a). Rivero et al. (2013) also studied the controlled release of propionic acid from chitosan films to dough.

7.4 Application as Shelf-Life Improver and as Carriers of Bioactive Compounds, Vitamins or Minerals

Actual challenges faced by the food industry involve the extension of food shelf-life without impairing the nutritious properties of food products and through the use of sustainable techniques (Díaz-Montes and Castro-Muñoz 2021). The food products available in the market for celiac population, particularly bakery stuffs, might have reduced nutritional and organoleptic quality due to the necessary change in formulation. Such nutrient deficiencies promote an unbalanced diet for GF consumers, especially regarding fibre, bioactive compounds, vitamins and minerals (Capriles et al. 2016). As a consequence, important efforts have been focused in diversifying and improving the offer of GF items with better nutritional characteristics (Genevois et al. 2020).

With the purpose of contributing to the development of healthy foods with long shelf-life, many emergent technologies have been explored in the last years. As was previously mentioned, edible films and coatings are one of the hurdles that have been explored. They are produced using polysaccharides, proteins, and lipids, and besides, they can support antioxidants, antimicrobials, vitamins, probiotics, minerals, flavouring, and colouring agents. The use of antioxidants, antimicrobials and other nutraceuticals supported in these edibles layers allows to control their location, their release and the matrix also exerts a physical protection that slows down their destruction. As a consequence, films and coatings can help to improve shelf-life and/or food quality (Gerschenson et al. 2018; Alzate et al. 2021). In particular, in the case of considering the probability of consumer's gluten intolerances, the use of edibles films must be adapted to this restriction, ensuring the absence of harmful proteins in the formulation. In this case, alternative proteins, starches, rice by-products or different hydrocolloids like alginate that have algal origin, can be used for films and coatings production (Senturk Parreidt et al. 2018a, b). In addition, edible films and coatings can contribute to enhance the nutritional properties of foods through the support of vitamins, probiotics, and other compounds.

In the next items and Table 7.2, there will be described some matrices mainly based on polysaccharides that were developed in the last years and that can be used

Table 7.2 Different GF edible films and coatings used in bakery products

Application	GF matrix	Active agent	Bakery stuff	Main effects	Shelf-life (t, T)	References
Coating	Groundnut oil	N.I.	GF flatbread	Slowing of staling rate	8 days 2 °C	Patil et al. (2019)
Coating	Corn starch, MC, soybean oil, glycerol	N.I.	Crackers	Reduction of the hydration kinetic in a high a_w environment	20 days 25 °C	Bravin et al. (2006)
Coating	Egg protein, hydrocolloid component, vegetable oil	N.I.	Sweet baked goods	Reduction of water migration rate between components	85 days 25 °C	De Pilli (2020)
Coating	*Lepidium sativum* seed gum	N.I.	Sorghum GF bread	Improvement of crust and overall quality in comparison with normal glazes	N.R.	Sahraiyan et al. (2020)
Coating	Okra mucilage	N.I.	Soft dough biscuits	Improvement of the crispiness	6 days 25 °C	Senanayake et al. (2021)
Coating	Candelilla wax (in sunflower oil), beeswax (in sunflower oil), HPMC	N.I.	Bread	Reductions of bread weight loss and the crumb firmness	14 days 25 °C	Chen et al. (2021)
Coating	Pectin, alginate and whey protein	N.I.	Mini-buns	Reduction of moisture loss and textural changes	N.R.	Nallan Chakravartula et al. (2019c)
Coating	Sodium alginate, whey, glycerol	Lactic acid bacteria	Bread	Reduction of mesophilic and facultative aerobic bacteria count protection against mycelium fungi of genera *Aspergillus* and *Penicillium*	5 days 28 °C	Gregirchak et al. (2020)
Coating	Egg white protein	Carvacrol, thymol, *trans*-cinnamaldehyde	Bread	High antifungal efficacy of coatings supporting thymol and carvacrol nanocomplexes	7 days 25 °C	Deseta et al. (2021)
Coating	Cassava starch, inverted sugar, sucrose	Soluble coffee, cocoa powder or propolis extract	Muffins	High antimicrobial action against mould and yeast maintenance of the global quality	87 days 25 °C	de Oliveira Melo Naponucena et al. (2019)

(continued)

Table 7.2 (continued)

Application	GF matrix	Active agent	Bakery stuff	Main effects	Shelf-life (t, T)	References
Coating	Sodium alginate or blends sodium alginate and whey protein concentrate	*Lactobacillus rhamnosus* GG	Pan bread	Improvement of the viability of *L. rhamnosus* GG No modification of textural, flavour and thermophysical properties of crust	7 days 25 °C	Soukoulis et al. (2014)
Coating	Potato starch, inverted sugar, sucrose	Potassium sorbate and/or citric acid	Mini panettone	Inhibition of mould/yeast grown	48 days 35 °C	Ferreira Saraiva et al. (2016)
Coating	Sodium alginate, whey protein, glycerol	*L. brevis*	GF cookies	Improvement nutritional quality without modifying physical and sensorial properties	30 days 35 °C	Chávez et al. (2022)
Coating	Mung bean starch, guar gum, sunflower seed oil	Grapefruit seed extract	Non-glutinous rice flour cakes	Improvement stability by retarding starch retrogradation and inhibiting *B. cereus* and *P. citrinum* growth	N.R.	Lee et al. (2020)
Film	Starch-based (tapioca, potato, corn), cellulose nanofiber.	N.I.	Muffin	Good performance as a liner to hold the batter and protect the muffins from sticking to the pan during baking. Film could be consumed	N.R.	Shih and Zhao (2021)
Film	MC, polyethylene glycol	Clove bud or oregano essential oil (Tween 80 addition)	Bread slices	Reduction of yeasts and moulds counts	15 days 25 °C	Otoni et al. (2014)
Film	Cellulose-derivative polymer	Cinnamaldehyde	Pastry dough (P d) and bread (B)	Inhibition of aerobic mesophilic, yeast and mould growth.	P d: 30 days 8 °C. B: 12 days 23 °C	Lopes et al. (2013)
Film	Chitosan	Apricot kernel essential oil	Bread	Inhibition of fungal growth	10 days 25 °C	Priyadarshi et al. (2018)
Film and coating	Chitosan-carboxymethyl cellulose-oleic acid	Zinc oxide nanoparticles	Sliced bread	Reduction of fungal growth and retard the staling rate	35 days 25 °C	Noshirvani et al. (2017)

NI not incorporated, *NR* not reported in the development of food products that need GF formulation. Many advances have been reported in relation to improve global quality of diverse traditional bakery products based on wheat using active edible films and coatings through the extension of microbial stability during storage (de Oliveira et al. 2019; Qian et al. 2021; Axel et al. 2017; Noshirvani et al. 2017), the maintenance of the crispiness and textural characteristic by reducing staling (Senanayake et al. 2021; Nallan Chakravartula et al. 2019c; Chen et al. 2021) and the increase of nutritional or functional properties, through probiotics or prebiotics incorporation (Zoghi et al. 2020; Fernándes et al. 2020). On the contrary, few studies were performed combining GF edible films or coatings on GF bakery products. Recently, Chavez et al. (2022) covered GF cookies with an edible coating based on sodium alginate (1% w/w), whey of milk protein (2% w/w) and glycerol (5% w/w) water solution supporting probiotics, *L. brevis* strain, improving functional value without affecting sensorial and physical properties. Another research (Lee et al. 2020), reported that cakes made with non-glutinous rice flour and coated with mung bean starch and guar gum slurry containing sunflower seed oil, decreased the hardness by 29% and the crystallisation rate by 24% compared with those of uncoated samples along storage at 25 °C. The authors concluded that edible coating retard the starch retrogradation in coated cakes. In the same study, the addition of 0.8% (w/w) grapefruit seed extract to coating exerted an effective antimicrobial activity against *B. cereus* and *P. citrinum* during rice cake storage. Similarly, Patil et al. (2019) demonstrated that staling rate was successfully retarded with the help of a groundnut oil coating on the surface of the GF flatbread during storage at 4 °C. Finally, Sahraiyan et al. (2020) analysed the effects of traditional glazes (oil, cheese powder, xanthan gum) on the physicochemical and sensory parameters of sorghum GF bread and were compared with *Lepidium sativum* seed gum coating. Results showed that application of novel glaze was better than the usual glazes to improve the crust and overall quality of GF bread.

7.4.1 Films and Coatings and WVP Control

Bravin et al. (2006) studied the development of emulsified edible films constituted by corn starch, MC and soybean oil. The techniques explored for deposition of the film forming solution were spreading or spraying. The presence of oil depressed the WVP. With this formulation, both techniques produced, in general, similar WVP. Atomization pressure of 2 bar and film thickness of 30 μm were identified as optimum for the application of edible coating to bakery products. Edible coating of previously described characteristics was applied for controlling moisture uptake in crackers submitted to RH of 65–85%. Crackers coated with this formulation showed a longer shelf-life due to the control of moisture transfer exerted by the film, confirming its potential for slowing the hydration rate in the RH range studied. In another study, Shih et al. (2011) developed edible films using various ratios of pullulan and rice wax up to 46.4% (w/w). Authors reported that water vapour barrier increased and hydration capacity decreased with a higher addition of rice wax helping to lengthen the shelf-life of food products. Several bio-polymeric matrices were analysed by Cando et al. (2017), who studied the production by casting technique of biodegradable films based on dispersions of a mix (50:50) of cassava, rice or potato starch and bovine gelatine. The total solid concentration of the dispersions was 2% (w/w) and glycerol was used as plasticiser. The films with cassava starch showed the lowest WVP. Nisar et al. (2018) developed antimicrobial films based on citrus pectin with the incorporation of different levels of clove bud essential oil. The inclusion of oil diminished the WVP and increased the deformability and heat stability of the films.

7.4.2 Films and Coatings. Weight Loss and Antimicrobial/Antioxidant Effect

Sadygova and Kozlov (2015) developed an edible foam for coating bakery products, with gram flour (5–15%), ashberry powder (5–10%), table salt (1–3%) and water up to 100%. The film was produced through drying at 55–65 °C for reducing the moisture content to 5–10%. This coating lengthens the shelf-life of bakery products helping to decrease microbiological count. Ferreira Saraiva et al. (2016) studied the application of edible coatings based on potato starch (46 g/kg), inverted sugar (14 g/kg) and sucrose (7 g/kg), with the purpose of reducing the preservatives added to mini panettones. The preservatives added to coating formulations were potassium sorbate (1 g/kg), citric acid (10 g/kg) and both additives (1 g/kg sorbate and 10 g/kg citric acid or 0.5 g/kg sorbate and 5 g/kg citric acid). Panettones without coating and additives showed the growth of mould and yeasts after 24 days of storage. On the contrary, the presence of films with both additives showed fungal growth only after 40 days. The authors concluded that the use as coatings of films with additives in concentrations lower than those normally used for these foods, increased their shelf-life.

Regarding active films added with natural preservatives, Nisar et al. (2018) showed that antimicrobial films based on citrus pectin with the incorporation of different levels of clove bud essential oil were effective against *S. aureus*, *E. coli and L. monocytogenes* when evaluated through the diffusion tests, showing a diameter increase from 18.50 to 30.27 mm, 12.53 to 21.20 mm and 14.67 to 26.43 mm, respectively, with the increase of oil concentration from 0.5% to 1.5%. The most sensible bacteria was *S. aureus*. According to Alzate et al. (2017) the addition of carvacrol, the main component of the oregano essential oil, to edible film formulation based on cassava starch and HPMC, highly improved the antimicrobial barrier action against *Z. bailii*, *L. plantarum*, and *P. fluorescens* in comparison with films containing only potassium sorbate. Recently, Mahcene et al. (2020) studied the use of sodium alginate to constitute films incorporated with essential oils of some medicinal plants (*R. officinalis* L, *A. herba alba Asso*, *O. basilicum* L and *M.*

pulegium L). The films showed a strong antibacterial effect against *Staphylococcus aureus* (ATCC 43300), *Escherichia coli* (ATCC 25922), *Salmonella enterica* (ATCC 14028), *Enterococcus faecium* (ATCC 35667), *Klebsiella pneumoniae* (ATCC 70060) and *Enterococcus faecalis* (ATCC 29212). The antioxidant capacity, reported as DPPH inhibition %, of the different films showed values of 4% for *M. pulegium*'s oil film to 23% for *O. basilicum* oil film in comparison with the control film which revealed no radical scavenging activity. The authors attributed these low values to the destruction of the active principles during film production and/or to the reaction of active principles with alginate.

Utama-ang et al. (2021) studied the microwave-assisted extraction (400 W, 1 min) of phenolic compounds from dried ginger and its incorporation (3.2% w/v) in a rice-based edible film. This edible film showed antioxidant activity due to the presence of 6-gingerol, 6-shogaol, paradol and zingerone. The incorporation to the formulation of 3.2% (w/v) ginger extract determined that the film showed antimicrobial activity against *S. mutans* DMST 18777. Yerramathi et al. (2021) developed a film based on alginate crosslinked with ferulic acid, for extending the shelf-life of different foods. The edible films developed showed an increasing antioxidant effect with the concentration of ferulic acid. Table 7.2 summarises the different GF active edible packaging used to improve the quality or extend the shelf-life of bakery products.

The effectiveness of the methods described in Table 7.2 depend on the food product characteristics (shape and size), the composition of the edible films and coatings, the physical properties (surface tension, density, and viscosity) (Andrade et al. 2012; Debeaufort and Voilley 2009), the processing method used and the sensory compatibility with the food (Restrepo et al. 2018).

7.4.3 Films and Coatings for Supporting Micronutrients/ Probiotics

In particular, edible films have been proposed for the support and protection of probiotics. Probiotics are defined as nonpathogenic living microorganisms that have beneficial effects on host health and disease prevention when administered in adequate amounts (Kunes and Kvetina 2016). Soukoulis et al. (2014) studied the application of film forming solutions based on 1% w/w sodium alginate or in blends of 0.5% w/w sodium alginate and 2% whey protein concentrate, to bread. These solutions contained the probiotic *Lactobacillus rhamnosus* GG, and after its application on the surface of the bread, a drying step (60 °C, 10 min or 180 °C, 2 min) gave origin to a film that did not affect visually the crust and did not affect bread staling. The presence of whey protein concentrate improved the viability of the lactobacilli during drying and also during bread storage. The authors reported that films based exclusively on sodium alginate increased the viability of lactobacilli under simulated gastro-intestinal and concluded that a slice of bread (3–40 g) can provide approximately 7 log CFU of lactobacilli, contributing to the development of more healthy foods. In another study, Altamirano-Fortoul et al. (2012) developed functional bread combining *L. acidophilus* encapsulation and starch based edible coating. The results demonstrated the ability of the coating to protect the probiotics during baking, allowing their survival. However, significant physicochemical changes were observed on the crust. Many other GF bio-polymeric matrices have been assays as carriers of probiotics to broaden the offer of functional foods and to improve probiotic viability during processing and storage (Zoghi et al. 2020).

Likewise, edible coatings may also act as carriers of nutrients. Caseins and whey proteins based matrices have been used to control the release or support of calcium, iron, vitamin D, A, E and folic acid in several food stuffs (Daniloski et al. 2021; Mei and Zhao 2003). Genevois et al. (2016) developed a refrigerated ready-to-eat food based on pumpkin and fortified with iron and ascorbic acid supported in a coating matrix, which helped to enhance their bioaccessibility at *in vitro* simulated lumen conditions. Edible folic acid-nanolaminates were obtained by the layer-by-layer technique using alginate and chitosan biopolymers while the vitamin was incorporated by post-diffusion (Acevedo-Fani et al. 2018). These systems were able to protect folic acid from degradation by UV irradiation whereas the release profiles were affected by pH level, being faster in simulated conditions of the small intestine (pH 7). In another work, Behjati and Yazdanpanah (2021) elaborated a nano-emulsion vitamin D_3 fortified edible film based on quince seed gum which promoted high stability of the vitamin. Therefore, the authors concluded that fortified edible films can be used in ready-to-eat food products to improve vitamin intake. Moreover, Vitamin C (L-(+)-ascorbic acid), with important antioxidant activity, could be retained and protected when was supported in an alginate edible coating (De'Nobili et al. 2017) or a high methoxyl pectin edible film (Pérez et al. 2009), constituting an effective strategy for reduce its degradation. The authors demonstrated that the immobilisation of water in the film network modulated vitamin loss.

7.5 Conclusions

GF edible films, coatings and toppings applied to bakery products provide protection against external factors that can alter their quality. Toppings are essential for flavour and determine the appearance of the product, providing certain short-term barrier protection. On the other hand, edible coatings and films are a great barrier that focuses on extending long-term protection and provide a way to incorporate active components, such as antimicrobials or antioxidants to prevent microbial and oxidative impairment. In addition, edible films and coatings also can improve the nutritional quality of GF bakeries, since they can support vitamins, minerals, probiotics, etc. Therefore, actual GF available products can become functional foods offering to consumers with disorders related to gluten intake, higher quality and more diversified foods. Thus, improved GF bakery could help to avoid the risk of a nutritional deficiency and to exert a positive effect on health beyond basic nutrition. Future research must be focused on studying the effects of different GF formulations and processing of edible films, coatings and toppings on the physicochemical, sensorial and nutritional properties of GF bakery products. In addition, the influence of the application methodology on such characteristics should be further explored in order to help the achievement of a greater insertion of these technologies in the food industry while contributing to the generation of healthy foods.

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