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Review

Edible packaging: Sustainable solutions and novel trends in food packaging

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ABSTRACT

Novel food packaging techniques are an important area of research to promote food quality and safety. There is a trend towards environmentally sustainable and edible forms of packaging. Edible packaging typically uses sustainable, biodegradable material that is applied as a consumable wrapping or coating around the food, which generates no waste. Numerous studies have recently investigated the importance of edible materials as an added value to packaged foods. Nanotechnology has emerged as a promising method to provide use of bioactives, antimicrobials, vitamins, antioxidants and nutrients to potentially increase the functionality of edible packaging. It can act as edible dispensers of food ingredients as encapsulants, nanofibers, nanoparticles and nanoemulsions. In this way, edible packaging serves as an active form of packaging. It plays an important role in packaged foods by desirably interacting with the food and providing technological functions such as releasing scavenging compounds (antimicrobials and antioxidants), and removing harmful gasses such as oxygen and water vapour which all can decrease products quality and shelf life. Active packaging can also contribute to maintaining the nutritive profile of packaged foods. In this review, authors present the latest information on new technological advances in edible food packaging, their novel applications and provide examples of recent studies where edible packaging possesses also an active role.

1. Introduction

Food packaging is an essential component of the food supply chain and is becoming a pivotal element of the final preparation process in food industries. Food packaging also plays an imperative role in society, protecting food and food products from potential damage and degradation while ensuring safety and hygiene, and actively reducing food waste. It is estimated that more than 30% of food produced is deposited in landfills due to spoilage during transportation and/or harvesting practices (Aguirre-Joya et al., 2018). Therefore, the application of adequate food packaging can assist in the reduction and prevention of the generation of food waste (Aguirre-Joya et al., 2018; Jeevahan et al., 2018; Naumovski, Ranadheera, Thomas, Georgousopoulou, & Mellor, 2017; Pooja Saklani, Nath, Kishor Das, & Singh, 2019). The appropriate selection of food packaging should also ensure no negative alterations in food quality (i.e. colour, taste), microorganism development, lipid oxidation or degradation of nutrients in the food (Daniloski et al., 2019; Jeevahan & Chandrasekaran, 2019; Umaraw et al., 2020).

Conventional packaging is commonly a one-time use item that is discarded upon reaching the consumer or after using the packed content. Some of the most common conventionally used materials in food packaging include paper, plastic, glass, steel, aluminium and different alloys. As such, conventional packaging poses a tremendous environmental burden despite relatively high recycling rates for some materials (over 20% recycling rate for certain paper and paperboard), while others such as various plastics are commonly recycled at low recycling rates (less than 20%) (Jeevahan & Chandrasekaran, 2019). One of the main issues is the non-sustainable nature of plastics, which are commonly

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derived from petroleum such as polyethylene, polypropylene, and polyethylene terephthalate are widely used due to their relatively easy shape-forming properties and lower weights than other materials (Ahmadi, Jahanban-Esfahlan, Ahmadi, Tabibiazar, & Mohammadifar, 2020; Allegra et al., 2017; Alvarez, Ponce, & Moreira, 2013; Vasile, 2018). Moreover, these materials are considered as not 'environmentally friendly' with the majority of them being non-renewable and also non-biodegradable, which subsequently end up in the landfills or oceans. Additionally, the use of these materials for food packaging has other, secondary negative environmental impacts, such as environmental pollution via generation of CO_2 and emission of other toxicants during their incineration, reliance on non-renewable petroleum reserves, and potential for harmful interactions between potential recycled/reused plastics and food (Aguirre-Joya et al., 2018; Jeevahan & Chandrasekaran, 2019; Jeevahan et al., 2018; Pooja Saklani et al., 2019).

Concurrently with the increased environmental concern regarding the growing rate of waste from packaging materials, current consumer demands and needs are directed towards more natural, high-quality, convenient and safer foods, posing a significant challenge to the food industry. There is an increasing demand for food packaging that does not increase pollution, and for products that are efficiently made by sustainable processes. Consequently, this has initiated an awareness and rise in research and industry focus on the development of sustainable, biodegradable, and edible materials that can improve food safety and increase food quality. Starches, cellulose derivatives, chitosan/chitin, gums, animal or plant-based proteins, and lipids can be incorporated into edible films to prolong shelf life. Such polymers deliver marketable advantages, such as biocompatibility, moisture and/or gas barrier properties, non-toxicity, and non-polluting characteristics (Mellinas et al., 2016). In this context, active, biodegradable and edible packaging materials are considered as one of the top priorities in the food industry due to the increased need for alternative packaging materials that are renewable, recyclable, easily degradable and require minimal or no need of disposal (Jeevahan & Chandrasekaran, 2019; Jeevahan et al., 2018). In order to be commercially viable, progress is required for edible film production to occur at an industrial scale. Issues still to be resolved include low resistance to gases and liquids, a lack of evaluation of edibility and biodegradability, and difficulty in manufacturing the edible films (Jeya et al., 2020). For example, edible packaging in the form of bags, cups, and coatings on food products are commercially available but not widely used. However, awareness of the applications of edible packaging has the potential to decrease waste in landfills, reduce pollution, and potentially assist with climate change.

2. Edible packaging

Edible packaging is regarded as a sustainable and biodegradable alternative in active food packaging field and provides food-quality optimisation compared to the conventional packaging. The usefulness of edible packaging is seen in its capacity to maintain food quality, extend shelf life, reduce waste, and to contribute to the economic efficiency of packaging materials. The development and application of edible films are among the most promising fields in food science due to their versatility, potential for being made from a variety of materials, and as carriers of different active substances such as antioxidant and/or antimicrobial agents. This has resulted in a significant increase in research activities in this area over the last decade, with several issues identified for consideration before adequate and safe industrial scale-up of edible food packaging (Aguirre-Joya et al., 2018; Restrepo et al., 2018). The materials of the food packaging is derived from edible ingredients such as natural polymers that can directly be consumed by humans without any potential health risk. These materials can be transformed into different forms of films and coatings without specific differences in their material composition but rather by changes in their thicknesses. Films are generally used in the production of wraps, pouches, bags, capsules, and casings, while coatings are applied directly on the food surface. In contrast to the films, the coatings are considered an integral part of the food product, and they are typically designed not to be removed from the food item (Aguirre-Joya et al., 2018). Therefore, proper selection of edible packaging components mainly depends on the food product required to be packed, and the composition of the material that the edible packaging is developed from, including the method of processing. Moreover, the packaging should have sensory compatibility with the packed food (Restrepo et al., 2018).

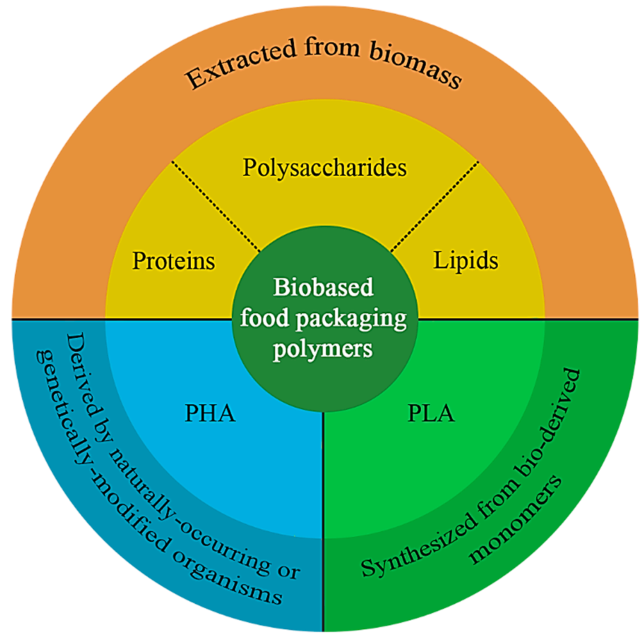

Fig. 1. Biobased materials for food packaging (PHA=PolyHydroxyAlkanoate; PLA=PolyLactic Acid).

2.1. Materials for edible packaging

There is ongoing research into the possibility of replacing synthetic and petroleum-based packaging with biologically-based, biodegradable materials. The use of bioengineered polymer resources for food packaging is an attractive packaging solution for many reasons; however, it is also a major food technology challenge (Ahmadi et al., 2020; Cerqueira, Pereira, da Silva Ramos, Teixeira, & Vicente, 2017; Erdem, Dıblan, & Kaya, 2019; García, Pérez, Piccirilli, & Verdini, 2020; Ramos et al., 2018; Sharma, Jafari, & Sharma, 2020; Williams & Patricia, 2018).

Bio-based and biodegradable materials can be categorised into three categories based on the sources from which they originate (Fig. 1) as follows:

- Materials developed from direct biomass/natural sources (proteins, polysaccharides, and lipids) (Pooja Saklani et al., 2019);
- Materials produced by microorganisms, usually belonging to specific types of polysaccharides (Ramos et al., 2018; Regubalan, Pandit, Maiti, Nadathur, & Mallick, 2018);
- Materials produced from bio-based monomers (Ramos et al., 2018; Regubalan et al., 2018).

Edible packaging materials are a subgroup of bio-based and biodegradable materials and have been extensively studied as an alternative to the traditional food packaging from the aspect of their film-formation properties. Biopolymers used as edible materials are classified as (Hanani, Roos, & Kerry, 2014; Jeevahan & Chandrasekaran, 2019; Jiménez, Requena, Vargas, Atarés, & Chiralt, 2018; Kumar & Neeraj, 2019; Shit & Shah, 2014):

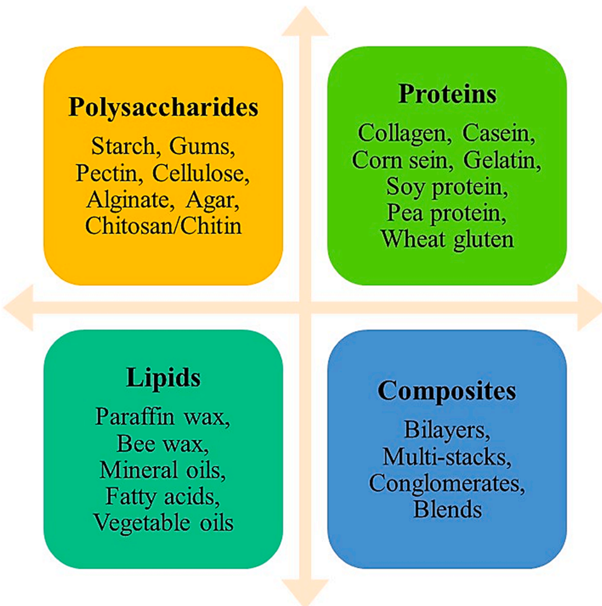

Fig. 2. Classification of edible materials.

- Polysaccharides (Arancibia, Giménez, López-Caballero, Gómez-Guillén, & Montero, 2014; Sánchez-Ortega et al., 2014; Thakur et al., 2019; Xie, Pollet, Halley, & Averous, 2014);
- Proteins (animal- or plant-based) (Cecchini, Spotti, Piagentini, Milt, & Carrara, 2017; Chen et al., 2019; Erdem et al., 2019; Galus & Lenart, 2019; Sarabandi et al., 2019; Schmid & Müller, 2019; Teixeira et al., 2014);
- Lipids (Fabra, Talens, Gavara, & Chiralt, 2012; Galus & Kadzińska, 2015; Sánchez-Ortega et al., 2014);
- Composites (Ramos et al., 2014; Talegaonkar, Sharma, Pandey, Mishra, & Wimmer, 2017).

These edible materials can be used in various food technology applications alone or in combination with other components (Fig. 2) (Bermúdez-Oria, Rodríguez-Gutiérrez, Rubio-Senent, Fernández-Prior, & Fernández-Bolaños, 2019; Dhall, 2013; Erdem et al., 2019; Łupina et al., 2019; Robledo et al., 2018; Siracusa et al., 2020). The term hydrocolloids is usually used as a mutual term for polysaccharides and proteins (Del-Valle, Hernández-Muñoz, Guarda, & Galotto, 2005; Osorio et al., 2018; Sabbah, Di Pierro, Dell'Olmo, Arciello, & Porta, 2019). Hydrocolloids possess long-chain hydrophilic polymers that form viscous dispersions or gels when dispersed in water (Jeevahan & Chandrasekaran, 2019; Sabbah et al., 2019; Valenzuela, Abugoch, & Tapia, 2013; Williams & Patricia, 2018).

Fig. 3. Benefits of edible packaging.

Edible films and coatings vary in their nature and origin with a number of different examples used such as chitosan coating (Alvarez et al., 2013), tomato-based (Du et al., 2008, 2009), cactus-mucilage (Del-Valle et al., 2005), quinoa protein/chitosan edible films (Robledo et al., 2018), apple-based (Du, Olsen, Avena-Bustillos, Friedman, & McHugh, 2011; Kadzińska, Bryś, Ostrowska-Ligęza, Estéve, & Janowicz, 2020; Ravishankar et al., 2012), banana starch (Pinzon et al., 2020; Restrepo et al., 2018), Aloe Vera, carrot film, rice, maize, potato and hibiscus films among others (Fangfang et al., 2020; Ravishankar et al., 2012).

3. Characteristics of edible packaging: advantages and limitations

Edible materials have many advantages over synthetic materials (Fig. 3), but the benefits of some of their characteristics remain relatively unclear (Dhall, 2013; Janjarasskul, Rauch, McCarthy, & Krochta, 2014; Jeevahan & Chandrasekaran, 2019; Madhu, Patel, Rao, & Sreedevi, 2018; Pooja Saklani et al., 2019; Shit & Shah, 2014). Edible packaging can function as a replacement and potential fortification of the layers at the outer surface of packaged products to prevent loss of moisture, aromas and ingredients out and between the foods, while at the same time, facilitating controlled exchange of essential gases involved in food product respiration (carbon dioxide, oxygen, and ethylene) (Galus & Kadzińska, 2019; Otoni et al., 2017). Edible packaging can also enhance the organoleptic properties of packaged foods, providing various flavourings and colourings as well as tailoring surface properties (i.e. hydrophobicity, hydrophilicity). Additionally, these can serve as a carrier of functional components with potentially added health or well-being benefits (Arnon-Rips & Poverenov, 2016; Dhall, 2013; Jeevahan & Chandrasekaran, 2019; Pooja Saklani et al., 2019). The hydrophilic nature of polysaccharides and proteins contribute to lower moisture resistance and barrier properties in comparison to lipids (Arnon-Rips & Poverenov, 2016). Polysaccharides are also suitable oxygen barriers while proteins show relatively good mechanical strength and can be used on fruits and vegetables to prevent damages during their transportation. In contrast, lipids show low water vapour permeability and relatively good moisture barrier properties. Lipid-based edible packaging is often opaque, waxy tasting, slippery, and usually preserves the colour, flavour, sweetener and salt concentrations (Galus & Kadzińska, 2015). However, lipids have poor mechanical and optical properties, as they are relatively thick and easily breakable. In addition, in some cases, there is poor adhesion of these materials to hydrophilic food surfaces (Aguirre-Joya et al., 2018; Arnon-Rips & Poverenov, 2016; Fabra et al., 2012; Pooja Saklani et al., 2019).

The composite edible packaging is proposed to improve the required properties depending on the final application to different food products. In most cases, the composite films consist of a protein, lipid layer and hydrocolloid components supported by a polysaccharide, or lipid material dispersed in a protein matrix or polysaccharide matrix (Aguirre-Joya et al., 2018; Chakravartula et al., 2019; Dhumal & Sarkar, 2018; Martiñon, Moreira, Castell-Perez, & Gomes, 2014; Pooja Saklani et al., 2019; Yousuf & Qadri, 2020). In these types of edible packaging, the combination of at least two constituents are proposed where the weakness of individual substance is compensated by adding the other component. For instance, the water vapour permeability of polysaccharides and proteins can be improved by adding lipids, forming edible composite that possesses both hydrophilic and hydrophobic properties. In addition, the mechanical strength of lipids is improved by adding proteins or polysaccharides, and even the overall mass transfer in edible material can be adjusted (Broumand, Emam-Djomeh, Hamedi, & Razavi, 2011; Chakravartula et al., 2019; Janjarasskul & Krochta, 2010; Jeevahan & Chandrasekaran, 2019; Majeed et al., 2013). In general, innovation in the edible packaging sector has the potential to become an everyday part of consumers' life. However, edible packaging will likely not solve the problem of plastic waste pollution, but, it can make a meaningful contribution.

3.1. Barrier functions of edible packaging

The moisture and oil absorption, oxygen transfer, flavour and odour change, or the migration of packaging components into the food are primarily responsible for the food quality (Dubey & Dubey, 2020). These characteristics also contribute to the mass transfer phenomena which occurs between foods (including some ingredients in the food product) and packaging materials, or between food and the environment. In the case of edible films and coatings, it is proposed that these products may prevent migration phenomena and contribute to better quality performance of the packed food products (Zhang et al., 2020). All barrier or transport properties of the edible films and coatings are also affected by the material composition and environmental conditions (relative humidity, temperature, pressure) at which the food products are processed and stored (Fritz, de Matos Fonseca, Trevisol, Fagundes, & Valencia, 2019; Han, 2014; Jeevahan & Chandrasekaran, 2019; Khan, Cakmak, Tavman, Schutyser, & Schroën, 2014; Saliu et al., 2019; Siracusa et al., 2020).

3.2. Deposition processes for edible packaging

Edible materials are usually applied on food by immersion, spraying and coating or by being formed prior to a film and used as a food wrap. The difference between an edible film and coating is that coatings are applied in liquid forms, while films are obtained as a solid sheet (i.e. laminates, multilayered films) and then applied to the food (Aguirre-Joya et al., 2018). Films are usually prepared by dissolving the edible material in water, alcohol, or a mixture of solvents. To enhance the flexibility and durability of these materials, additives such as plasticisers are incorporated in matrix material (Murrieta-Martínez et al., 2019; Otoni et al., 2017). In addition, some additives with unique functionality could be added such as antimicrobial agents, colours, and flavouring, depending on the final application of the edible material (Bilal, Zhao, & Iqbal, 2020; Sharma, Shehin, Kaur, & Vyas, 2019). The type of edible packaging solution and application method mainly depends on the surface properties of the food product that should be covered (wettability, contact angle, surface tension (Aguirre-Joya et al., 2018; Kumar, Mukherjee, & Dutta, 2020; Osorio et al., 2018; Park et al., 2017; Robledo et al., 2018; Vasile, 2018).

Edible coatings are applied directly onto the food surface from liquid suspension, emulsion or powder form. This application of the edible coating solution on food is followed by an adhesion process requiring diffusion between both the coating solution and the surface area of the food product (Senturk Parreidt, Schmid, & Müller, 2018). Some methods for application of edible coatings on food products are dipping, spraying, brushing, fluidised bed processing, and the panning method (Andrade, Skurtys, & Osorio, 2012; Bastarrachea, Wong, Roman, Lin, & Goddard, 2015; Fritz et al., 2019; Suhag, Kumar, Petkoska, & Upadhyay, 2020).

For the production of edible films, in general, two types of processes exist: wet and dry processes. The wet process (casting) requires solvents for the solution and dispersion of the polymer onto a flat surface, followed by drying under controlled conditions which results in the formation of film (Aguirre-Joya et al., 2018; Suhag et al., 2020). Since the final product should be edible and biodegradable, only ethanol and water or their combination are adequate solvents. The production of edible films by dry methods includes extrusion, injection, blow-moulding, and heat-pressing processes. In general, dry processing utilises thermoplastic materials that can be processed into films by applying various thermal-mechanical processing techniques. This process is advantageous compared to wet process due to the absence of solvents, easy handling of high viscous polymers and a broad range of processing techniques. In order to improve the film performance, in most cases, the method of lamination is used (Janjarasskul & Krochta, 2010).

The multilayered structures and the combination of characteristics of various ingredients into a sheet is also a preferred packaging option due to many advantages such as higher toughness and tensile strength compared to the individual ingredients (Aguirre-Joya et al., 2018; Kumar & Neeraj, 2019; Mkandawire & Aryee, 2018; Pooja Saklani et al., 2019; Regubalan et al., 2018; Suhag et al., 2020). Numerus studies have explained the utilisation of various deposition methods for coating applications for food products to increase their shelf life and enhance their quality and safety as well (Atieno, Owino, Ateka, & Ambuko, 2019; Dong & Wang, 2018; Suhag et al., 2020).

4. Edible packaging as a carrier for functional bioactive compounds

Active and smart packaging has been used worldwide, mostly in the United States, Australia and Japan, while in Europe it was introduced after European Union (EU) legislation changes (Regulation EC, 1935/2004). The EU definition of active packaging (as defined in the European regulation [EC] No. 450/2009) states that active packaging systems are designed to "deliberately incorporate components that would release or absorb substances into or from the packaged food or the environment surrounding the food." In this way, they "intend to extend the shelf-life or to maintain or improve the condition of packaged food" (Yildirim et al., 2018). One of the significant emerging functions of edible packaging materials is their use as a matrix and carrier of different functional additives that can provide additional nutritive and health benefits to the packaged food (Broumand et al., 2011). Usually, different antimicrobial and antioxidant substances, prebiotics or other nutrients can be added to edible matrices to extend shelf life and/or increase the nutritional value of the final packaged food (Janjarasskul & Krochta, 2010; Odila Pereira et al., 2019). Several different substances could be incorporated into edible films to enhance structural, mechanical and handling properties or to provide active functions to the coating (Benbettaïeb, Karbowiak, & Debeaufort, 2019; Janjarasskul & Krochta, 2010; Valencia, Luciano, & Fritz, 2019; Vilela et al., 2018; Yousuf & Qadri, 2020).

4.1. Nutraceuticals in edible packaging

Nutraceuticals are compounds that are usually derived from food sources and can provide health benefits (Nasri, Baradaran, Shirzad, & Rafieian-Kopaei, 2014). Their incorporation into the food coatings can potentially compensate for the loss of nutrients that usually occur during food processing, or increase the nutrient composition of the newly coated food products. Edible matrices also appear to be suitable carrier materials for nutraceuticals as in some cases, direct use of nutraceuticals on food is not recommended due to their fast degradation or potential for production of undesired reactions in foods and consumers if taken in large quantities (Arnon-Rips & Poverenov, 2016; Dhall, 2013). The main influence of the nutraceuticals besides being a source of nutrients and energy is to provide potential beneficial health effects (Chauhan, Kumar, Kalam, & Ansari, 2013; Khorasani, Danaei, & Mozafari, 2018). In the literature, there are some nutraceutical compounds that have a positive influence on the human health, such as ascorbic acid (antioxidant), pectin (cardiovascular support), casein phosphopeptides (anti-atherosclerotic), omega fatty acids (anti-inflammatory), polyphenols (antioxidant and many other benefits), capsaicin (anticarcinogenic), beta-carotene (enhance the immune system, protect from age-related macular degeneration) to name a few (Du et al., 2011; Gul et al., 2015; Khorasani et al., 2018; Shinde, Bangar, Deshmukh, & Kumbhar, 2014).

4.2. Antioxidants and antimicrobials in edible packaging

Antioxidants can be added to edible materials to delay the rate of oxidation reactions and to increase food safety and quality (Munialo, Naumovski, Sergi, Stewart, & Mellor, 2019; Sabaghi, Maghsoudlou, Khomeiri, & Ziaiifar, 2015; Vasile, 2018). These compounds can suppress the activity of free radicals via several different pathways such as acting as scavengers of free radicals (i.e. glutathione), chain-breaking antioxidants neutralising the intermediate peroxyl radicals (i.e. ascorbic acid) and preventative antioxidants that can bind to certain metal cations (i.e. albumin). Therefore, with the use of antioxidants, there is a great potential the food products to be protected from damaging oxidative reactions, such as colour changes (i.e. enzymatic oxidation), altered flavours and odours (i.e. oxidative rancidity), as well as reduce structural modifications (i.e. softening) with time and potential nutritional losses (Arnon-Rips & Poverenov, 2016). Examples of 'natural-origin' antioxidants include plant extracts, essential oils, α-tocopherol, ascorbic, and citric acid, bee pollen, propolis and are all widely used individually or combined (Benbettaïeb et al., 2019; Espitia & Otoni, 2018; Janjarasskul & Krochta, 2010; Kumar, Ojha, & Singh, 2019; Munialo et al., 2019; Pires et al., 2013; Vuong, 2017). Plant extracts are often used in food packaging (Kumar et al., 2019; Munteanu & Vasile, 2020; Valdés et al., 2015; Yun et al., 2019), as among which pomegranate peel/dried extract (Kumar et al., 2019), and quince seed mucilage (Jouki, Yazdi, Mortazavi, & Koocheki, 2014), grape seed extract (Xiong, Chen, Warner, & Fang, 2020), green tea extract (Sabaghi et al., 2015), mint extracts (Raghav & Saini, 2018), black chokeberry extract (Kim, Baek, & Song, 2018) are on the top of the list. Recently, essential oils extracted from plants have been added as ingredients to the edible film formulations. These extracts have several bioactive compounds that can provide films with specific characteristics, but the most important is to be safe and edible. Such types of active packaging effectively extend food shelf life and contribute to the quality and safety of the packed content. Use of essential oils as substitutes for chemical antimicrobial agents can enhance the microbiological shelf-life of food products. Several studies have indicated beneficial antimicrobial effects against different types of microorganisms including human pathogens. The incorporation of these natural compounds into the product formulation or packaging materials not only inhibit fungal growth, but can also enhance oxidation stability. Along with a beneficial activity, essential oils may also affect the food organoleptic features and potentially act as flavour component (Arnon-Rips & Poverenov, 2016; Gavahian, Chu, Lorenzo, Mousavi Khaneghah, & Barba, 2020; Pavli et al., 2019).

Edible films and coatings can also be an efficient carrier of live microorganisms. Namely, incorporation of probiotics in the edible material, such as Lactic acid bacteria (LAB) or yeasts like *Saccharomyces cerevisiae* var. *boulardii*, *Debaryomyces hansenii, Torulaspora delbrueckii, Kluyveromyces lactis, Yarrowia lipolytica, S. cerevisiae, Kluyveromyces marxianus,* or *Kluyveromyces lodderae* can result in positive effects during processing and storage of food products. Different methods, such as microencapsulation or spray drying methods are used to incorporate microorganisms into these edible films and coatings that affect the viability and effective delivery of the microorganism within the polymer matrix (Kapetanakou & Skandamis, 2016; Pandhi, Kumar, & Alam, 2019; Vasile, 2018). Different studies have revealed that incorporation of microorganisms with antimicrobial properties limits the growth of pathogens when used for food packaging (Cui, Yuan, Li, & Lin, 2017; Kapetanakou & Skandamis, 2016; Siracusa et al., 2020).

Antifungal (Robledo et al., 2018; Sabaghi et al., 2015), antiviral (Falcó et al., 2019; Falcó, Randazzo, Sánchez, López-Rubio, & Fabra, 2019; Randazzo, Fabra, Falcó, López-Rubio, & Sánchez, 2018), and antimicrobial agents (Salvia-Trujillo, Rojas-Graü, Soliva-Fortuny, & Martín-Belloso, 2015), enhance the shelf life of foods and can be derived from natural or synthetic substances (Arancibia et al., 2014; Kumar et al., 2020; Rudra, Gundewadi, & Sharma, 2020; Sharma et al., 2020). According to many of these studies, essential and cold-pressed oils exhibited selective antibacterial and antifungal effect against food spoilage fungi once added in the edible film: *Fusarium graminearum*, *Penicillium corylophilum*, *Aspergillus brasiliensis;* and some potential pathogenic food bacteria, such as *Staphylococcus aureus, Escherichia coli, Listeria monocytogenes* or against *Pseudomonas aeruginosa* (Arancibia et al., 2014; Kumar et al., 2020; Rudra et al., 2020; Salvia-Trujillo et al., 2015; Vasile, 2018). Namely, antifungal and antiviral effects of green tea extract were confirmed on nuts and berries, respectively, against some foodborne pathogens like human noroviruses, hepatitis A virus (Falcó et al., 2019a, 2019b; Randazzo et al., 2018; Sabaghi et al., 2015).

The most widely used antimicrobial substances include organic acids (acetic, benzoic, citric, fumaric, lactic, malic, propionic, sorbic, succinic, and tartaric acid), polypeptides (lysozyme, peroxidase, lactoferrin, nisin), essential oils (oregano, lemongrass, cinnamon, tea tree, clove, pimento, thyme, calendula, basil, rosemary, bergamot, sage, garlic, etc.) (Donsì et al., 2015; Espitia et al., 2014; Kadzińska et al., 2020; Salvia-Trujillo et al., 2015; Šuput et al., 2016; Teixeira et al., 2014; Wu et al., 2015; Xiong et al., 2020). Antimicrobial food nanocarriers are also suitable for controlling spoilage and growth of pathogenic microorganisms in foodstuff (Arnon-Rips & Poverenov, 2016; Blanco-Padilla, Soto, Hernández Iturriaga, & Mendoza, 2014; Dinika & Utama, 2019; Dogra et al., 2015; Moradi, Barati, Salehi, Tonelli, & Hamedi, 2019; Noshirvani, Ghanbarzadeh, Mokarram, & Hashemi, 2017; Pinzon et al., 2020; Restrepo et al., 2018; Santos et al., 2018; Tomadoni, Moreira, Pereda, & Ponce, 2018). The (nano)carriers of antimicrobials are usually reported as nanoemulsions, nanoliposomes, nanoparticles, and nanofibers, and their incorporation into edible matrices effectively controls and maintains the function of the antimicrobials by protecting their fast diffusion into the food products (Arnon-Rips & Poverenov, 2016; Dhall, 2013; Du et al., 2008, 2009; Jin, Liu, Zhang, & Hicks, 2009; Pooja Saklani et al., 2019). The incorporation of active compounds into edibles improved drastically with the development of novel nanotechnologies, where the actives can be in micro- and nano-dimensions and different shapes. For instance, the actives are being incorporated in matrices as (nano)-liposomes, nanoemulsions, nanoparticles, nanofibers or as layer-by-layer technique (Aguirre-Joya et al., 2018; Arnon-Rips & Poverenov, 2016; Kumar et al., 2020).

Due to their small dimensions, nanomaterials are able to attach to many biological molecules with greater efficiency. The antimicrobial activity of nanoparticles, in general, is described as: directly interactions with microbial cells and interruption of the transmembrane electron transfer, disrupting/penetrating the cell envelope, oxidizing cell components, producing secondary products as reactive oxygen species or dissolved heavy metal ions (Vasile, 2018). Nanoparticles like TiO_2 show efficacy on bactericidal and fungicidal effect against *Salmonella choleraesius, Vibrio parahaemoliticus, Staphylocous aureus, Diaporthe actinide, Penicilinum expansum.* In addition, ZnO is efficient both against Gram-positive and Gram-negative bacteria while nano-ZnO coated films exhibit antimicrobial effects against *L. Monocytes* and *S. Enteritis.* The antibacterial activity of Ag ion is reduced by protein-rich food and can bind to cysteine, methionine, lysine, and arginine. Its antimicrobial activity is explained by adhesion to the cell surface, degrading lipopolysaccharides, damaging the membranes and increasing permeability. The Ag ions can be released to prevent food spoilage as they are effective against bacteria like, *E. Coli, Enterococcus faecalis, Staphylococcus aureus, Epidermidis, Vibrio cholera, Pseudomonas aeruginosa, Bacillus anthracis, Proteus mirabilis, Salmonella enterica* typhmurium, *Listeria monocytogenes*, and *Klebsiella pneumoniae* (Kumar et al., 2020; Sharma et al., 2020; Vasile, 2018).

4.3. Other additives in edible packaging

The function of other additives in edible materials are relatively known but have shown to have good processing or desired final properties of the food products. Some of these materials include plasticisers, emulsifiers and texture enhancers (Aguirre-Joya et al., 2018). Most polysaccharide- and protein-based films and coatings are brittle, and to overcome this issue and make them as flexible edible films, plasticisers are incorporated within the film structure (Regubalan et al., 2018). Some of the most commonly used plasticisers include monosaccharides, oligosaccharides, polyols and lipids (Xie, Pollet, Halley, & Averous, 2014). With a proper selection of a plasticiser for a given biopolymer, optimisation of the film mechanical properties with a minimum increase in film permeability could be achieved, as well as enhancement in the film flexibility and resilience is possible (Janjarasskul & Krochta, 2010; Kuorwel, Cran, Sonneveld, Miltz, & Bigger, 2011; Xie et al., 2014).

Emulsifiers are surface-active compounds with both polar and nonpolar characteristics, capable of modifying interfacial energy at the interface of immiscible systems (water–lipid) (Janjarasskul & Krochta, 2010). In general, these compounds are used for the formation and stabilisation of well-dispersed lipid particles in composite emulsion films or to achieve sufficient surface wettability to ensure proper surface coverage and adhesion to the coated surface (Taarji et al., 2020). Sugar esters and glycerol monooleate, for example, solubilise the essential oil in the aqueous phase resulting in a high antimicrobial activity (Aguirre-Joya et al., 2018). Other potential emulsifiers include acetylated monoglyceride, lecithin, glycerol monopalmitate, glycerol monostearate, polysorbates, sodium lauryl sulfate, sodium stearoyl lactylate, and sorbitan monooleate and sorbitan monostearate (Mendes et al., 2020). In addition, calcium salts could be used as texture enhancers as these salts interact with carboxylated polymers and form a cross-linked network that increases the firmness of the product. Anti-browning agents are also widely used in edible coatings for packaging fruits and vegetables and their products (Arnon-Rips & Poverenov, 2016; Vasile, 2018).

Flavour and aroma components of foods may be altered or escape during the processing or storage time due to their volatile nature. Flavouring substances can be extracted via physical, enzymatic, or microbiological methods from animal, marine and plant sources. Some examples of commonly used plants for the development of flavour or aroma include oregano, cinnamon, curcumin, clove, rosemary, in addition to synthetic flavours. Natural aromatic substances are becoming more attractive in the food industry due to increased consumer awareness as being perceived as natural and healthy foods. Interestingly, some flavours are synthesised by living organisms as a defence mechanism or as secondary metabolites, such as flowers (jasmine), herbs (rosemary), buds (clove), leaves (eucalyptus), fruits (citrus), barks (cinnamon), seeds (cardamom), or roots (ginger) (Arnon-Rips & Poverenov, 2016; Burgos, Mellinas, García-Serna, & Jiménez, 2017).

5. Nanotechnology in favour of edible packaging

Nanotechnology is enabling the novel development of nanoscale edible coatings (around 5 nm thickness) which could be used for packaging meats, cheese, fruit, vegetables, confectionery, bakery goods, and fast food products. The advantage of nanoscale edible coatings is that it provides a barrier to moisture and controls gaseous exchange. At the same time, nano-coatings can act as a vehicle to deliver colours, flavours, antioxidants, enzymes and anti-browning agents, and could also increase the shelf life of manufactured foods (Chaturvedi & Dave, 2020; Gardesh et al., 2016; McClements & Xiao, 2017; Ramos et al., 2014; Shafiq, Anjum, Hano, Anjum, & Abbasi, 2020; Vasile, 2018). The potential benefits of nanomaterials are different from the same materials in bulk or with macroscopic dimensions. Food-based nanomaterials have been part of food processing for centuries since many food structures naturally exist at the nanoscale dimensions. Usage of nanomaterials in the food industry covers many aspects such as food safety, nanosensors, nutrients delivery systems, and enhancement in bioavailability, new materials for pathogen detection and packaging materials. Typically, nanopackaging is produced with nanoparticles/nanomaterials that exhibit chemical and physical properties that differ from those of larger particles (Shafiq et al., 2020; Wardhono et al., 2019).

Nevertheless, several authors emphasise the usage of the term 'nanofood' to describe food that has been cultivated, produced, processed or packaged using nanotechnology tools, or to which nanomaterials have been added. The goal of nanofood is to improve food safety, quality, enhance the nutritional health benefits and extend the shelf-life by cost-effective means (GuhanNath, Aaron, Raj, & Ranganathan, 2014; Pires et al., 2013). The use of nanostructures such as nanohydrogels, nanoemulsions, nanoparticles for the incorporation of bioactives are expected to increase the potential applications of edible packaging as active and further enhance smart packaging options (Cerqueira et al., 2017; González-Reza et al., 2018; Noshirvani et al., 2017; Valencia et al., 2019; Wardhono et al., 2019).

5.1. Nanoparticles

Nanoparticles usually provide both enhancements of mechanical, physical and barrier properties of the edible films and coatings, and they can also serve as encapsulating systems for active components. The incorporation of nanoparticles into edible materials serve as delivery systems for active agents. In most cases, this has led to the development of a variety of nanoparticle reinforced edible materials so-called "nanocomposites" (Chaturvedi & Dave, 2020; Liu, Zhang, Sohal, Bello, & Chen, 2019; Salmieri et al., 2014; Shafiq et al., 2020; Sohal, O'Fallon, Gaines, Demokritou, & Bello, 2018; Talegaonkar et al., 2017; Vasile, 2018). Furthermore, edible films containing nanoparticles can be customised and achieve suitable outcomes for the packaging industry including better mechanical properties and customised barrier performance (Arnon-Rips & Poverenov, 2016; Brandelli, Brum, & dos Santos, 2016; Hannon, Kerry, Cruz-Romero, Morris, & Cummins, 2015; Kapetanakou & Skandamis, 2016; Khalaf, Sharoba, El-Tanahi, & Morsy, 2013; Talegaonkar et al., 2017; Trujillo, Ávalos, Granda, Guerra, & País-Chanfrau, 2016; Valdés et al., 2015). The most used nanoparticles include silver, gold, iron, zinc oxide, silicon dioxide, titanium dioxide, titanium nitride, alumina, iron oxide, copper, copper oxides, gallium and palladium (Gudadhe et al., 2013; Rai et al., 2014; Sohal et al., 2018; Xing et al., 2019). However, nanoparticles can also be derived from nonmetals, clays or organic materials (Wardhono et al., 2019). The nanoparticles produced from food-grade biopolymers such as polysaccharides, proteins or natural bioactive compounds (e.g. curcumin, lipids) are also reported in the literature. Some examples of nanoparticles used in edible packaging include nanostarch, starch nanocrystals, chitosan, nanoclay, and nanocelluloses (Andrade et al., 2012; Azeredo et al., 2019; Ceylan, Sengor, & Yilmaz, 2018; Dammak & do Amaral Sobral, 2018; McClements & Xiao, 2017; Wardhono et al., 2019; Zambrano-Zaragoza et al., 2018). Several natural compounds with antimicrobial and antifungal activities have also been encapsulated in nanoparticles (Čakarević et al., 2020; Krepker et al., 2017). Combinations of nanoparticles have been used as a solution for cases when more than one active functionality is required in the food packaging, and examples include combinations of chitin and chitosan nanoparticles, zein nanoparticles coated with carboxymethyl chitosan for encapsulation of vitamin D3 and others (Luo, Teng, & Wang, 2012). In general, antimicrobial nanoparticles possess similar properties that make them effective against microorganisms which may eventually be detrimental for human cells (Sohal et al., 2018; Xing et al., 2019). Their incorporation in edible materials or preparation of nanocomposite for packaging solution should be taken with caution as their small size increases the potential for migration into foods (due to their larger surface area), thus, increasing the possibility of cell penetration and free movement within the body. For example, 20 nm Ag nanoparticles have been reported to be more toxic to lung tissue compared to 100 nm Ag nanoparticles (Azeredo et al., 2019; Liao, Li, & Tjong, 2019).

5.2. Nanocomposites

Nanocomposites are systems that are customised to fit the final application, and the customisation is usually based on the type, geometry and surface chemistry of the nanofiller (nano-reinforcement) and the type, content and chemical modification of the edible polymer matrix. The processing steps and conditions of composites' preparation is also an important factor that determines the final nanocomposite properties (Vasile, 2018). In this context, there are cases of nanocomposites as a mix of natural fibres, nanoclay particles embedded in suitable biopolymer matrix resulting in a hybrid material with improved barrier properties which after their use can be composted and added to the soil (Majeed et al., 2013). The current nanotechnology applications in food science also offer detection of food pathogens through built-in nanosensors that are quick, sensitive and operate via less labour-intensive procedures (Majeed et al., 2013). Furthermore, nanofibers are ultrathin structures with diameters below 100 nm and are produced mostly by electrospinning method from materials such as carbohydrates, proteins, lipids. The nanofibers possess high surface-to-volume ratios that are important for high efficiency of delivering active substances (Johansson et al., 2012). Several studies have already indicated that nanofibers with antimicrobial benefits are successful in active packaging systems (Vasile, 2018). Additionally, it was also reported that nanocellulose crystals and fibres could effectively improve mechanical and physical properties of edible films and coatings. Bio-based natural fibres as reinforcement materials are classified according to their origin as leaf, fruit, and seed-hair fibres and have been reported as reinforcing agents for different polymer matrices (Majeed et al., 2013).

5.3. Encapsulation technologies

Encapsulation technologies are usually used to protect flavours and aromas from external interactions and provide a controlled release to the packaged food. In the case of encapsulation of hydrophobic active agents, usually hydrophilic materials (i.e. polysaccharides, proteins) are used, while lipids or other polymers with hydrophobic character are used for encapsulation of hydrophilic compounds. According to their dimensions, encapsulated forms are declared as macro-, micro-, and nano-capsules (Donsì, Annunziata, Sessa, & Ferrari, 2011). Micro- and nano-encapsulation of active compounds (enzymes, probiotic, prebiotic, vitamins, antioxidants, omega-3-fatty acids) with edible coatings may contribute to controlled release under specific conditions (moisture, heat, pressure or other conditions and enhance their stability and viability) (Makwana, Choudhary, Dogra, Kohli, & Haddock, 2014). Nanoencapsulation is a technology that is used for packing substances in capsules, with sizes in nanometre dimensions, and the capsule actually enables the final product functionality, such as controlled release of the core active substance (Ceylan et al., 2018; Pabast, Shariatifar, Beikzadeh, & Jahed, 2018). Nanoencapsulation protection of compounds such as vitamins, antioxidants, antimicrobial, or antifungal chemicals, as well as proteins, probiotics, lipids or carbohydrates, has been used for production of functional foods with enhanced functionality, safety and stability (Blanco-Padilla et al., 2014; Cushen, Kerry, Morris, Cruz-Romero, & Cummins, 2012; Donsì, 2018).

Nanoemulsions also allow the proper delivery of bioactive agents, increased bioavailability, and better stability of these compounds. Therefore, delivery of active agents provides food products with better physiological properties, microbiological protection, and improves the products' nutritional values and organoleptic properties (Galus & Kadzińska, 2015; Kim, Oh, Lee, Song, & Min, 2014; Robledo et al., 2018). The nanoemulsion is a system formed by two immiscible liquids in which one is dispersed homogenously in the other, in the form of globules in nanometer sizes (50–500 nm). They are different compared to coarse emulsions due to their dimensions, and consequently, differ in their applications. In addition, due to a higher ratio of droplet surface per mass unit, nanoemulsions have high delivery/encapsulation ability, and their activity and bioavailability of an active agent are increased upon nanoemulsification (Hasan, Ferrentino, & Scampicchio, 2020; Xiong, Li, Warner, & Fang, 2020). The most common application of nanoemulsions in the food industry, and particularly in packaging is to deliver the active agents to solid foods, encapsulated essential oils, and nanoemulsified edible materials. Incorporation of essential oils into edible materials in a nanoemulsion form can also reduce their sensory impact and potentially minimise the essential oil concentration required for antimicrobial activity by increasing its accessibility. Nanoemulsions have also been used to encapsulate antimicrobial compounds that extend the food shelf life and increase food safety. They can be either directly incorporated into food systems (i.e. functional food) but also entrapped in polymer matrices to produce active (edible) packaging (Kumar et al., 2020; Shafiq et al., 2020).

Nanoliposomes are spherical core-shell nanostructures, where hydrophobic hydrocarbon tails of phospholipids are incorporated into a lipid bilayer, and the polar head groups are directed to the aqueous phases of the inner and outer media. Liposomes structures can encapsulate, deliver, and release hydrophilic and hydrophobic as well as amphiphilic active materials (Khorasani et al., 2018). The utilisation of liposome has also been shown to be another promising encapsulating material that increases the antimicrobial efficacy of the essential oils (Wu et al., 2015). In the food industry, nanoliposomes are being produced by natural sources such as egg, soy or milk that contained phospholipids with biological activity (Ota et al., 2018; Pabast et al., 2018; Sarabandi et al., 2019; Wu et al., 2015).

5.4. Nanolamination and layer-by-layer deposition

A nanolaminate consists of two or more layers of material with nanometre dimensions that are physically or chemically bonded to each other. Edible coatings and films are currently used on a wide variety of foods, including fruits, vegetables, meats, chocolate, candies, bakery products, and deep-fried potatoes. These coatings serve as moisture-, lipid-, and gas- barriers improving the texture of the food or serving as carriers of functional agents such as colours, flavours, antioxidants, nutrients, and antimicrobials. Coated foods with nanolaminates are usually prepared by dipping method in a series of solutions containing substances that will be absorbed by the food surface or spraying substances onto the food surface. The implementation of layer-by-layer methods allows the build-up of active films/coatings over the food product with precise nano-level tuning of their properties (Dhall, 2013). Edible coatings prepared by the layer-by-layer approach, in general, have advanced mechanical properties in comparison to the blended films. They usually provide excellent adhesion to the coated surface and between layers, appropriate firmness, sometimes antimicrobial benefit, gloss, colour, control the ripening rate and off-flavours. This technique could provide a good combination of lipids and hydrocolloids (Arnon-Rips & Poverenov, 2016; Chakravartula, Cevoli, Balestra, Fabbri, & Dalla Rosa, 2019; Hosseini, Shojaee-Aliabadi, Hosseini, & Mirmoghtadaie, 2017).

Layer-by-layer edible films and coatings are an alternate deposition of various polymeric films from edible materials in order to produce multilayers with controlled and desired properties (Bilbao-Sainz et al., 2018). This technique of altering the materials' features in a manner to manipulate its properties, enables the incorporation of a wide range of functional and active substances. The multilayered stack could be developed from food-grade materials (proteins, polysaccharides, lipids) and includes a variety of functional agents (antimicrobials, antioxidants, flavours) that enhance the food stability, safety and quality (Arnon-Rips & Poverenov, 2016; Bhagath & Manjula, 2019; Dhall, 2013; Jiang, Neetoo, & Chen, 2011; Poverenov, Rutenberg, Danino, Horev, & Rodov, 2014).

5.5. Remarks: Are nanosized particles safe?

Despite rapid developments in food nanotechnology, little is known about the occurrence, fate, and toxicity of nano-sized particles. Nanotechnology-derived food ingredients, food additives and food contact materials have been reported for potential implications for consumer safety and regulatory controls (GuhanNath et al., 2014; Hannon et al., 2015; Rai et al., 2014; Trujillo et al., 2016). Therefore, strict rules and policies should be implemented and enforced in the food industry. New approaches and standardised test procedures to study the impact of nanoparticles on living cells are urgently needed for the evaluation of potential hazards relating to human exposure to nanoparticles originating from food. Despite this, it is widely anticipated that nanotechnology-derived food products will be available increasingly to consumers worldwide in the coming years (Chaturvedi & Dave, 2020; Mlalila, Kadam, Swai, & Hilonga, 2016).

6. Applications of edible packaging

Edible packaging could be a potential packaging solution for many types of food. To date, there are data indicating that edible packaging has been successfully applied on meat, grains, nuts, cheese, bakery, confectioneries, fruits and vegetables (intact or fresh-cut) and will be briefly described below. The selection of edible packaging mainly is determined by the type of food that is packed as well as by storage time and conditions (Aguirre-Joya et al., 2018; Jeevahan & Chandrasekaran, 2019; Sharma et al., 2020).

Table 1
Applications of edible packaging options for fruits and vegetables.

Food product	Edible materials	Beneficial effect	Reference
Fruits and vegetables			
Cherry tomato	Edible film incorporated with chitosan and liposome encapsulation of Artemisia Annua oil. Edible coating based on nanoemulsion-thymol-quinoa protein/chitosan.	Inactivation of *Escherichia coli* O157:H7. Inhibition of *Botrytis cinerea*.	Cui et al. (2017); Robledo et al. (2018)
Tomato	Aloe vera based edible coating.	Delayed ripening and extended shelf life (up to 39 days compared to 19 days for control sample).	Athmaselvi et al. (2013)
Cucumber	Corn starch and mint (*Mentha viridis L.*) extract edible coating.	Enhancement of shelf life and quality stored at room temperature/low temperature (25 °C/10 °C).	Raghav and Saini (2018)
Brocolli (fresh cut)	Chitosan coatings with bioactives: tea tree, rosemary, pollen and propolis, pomegranate and resveratrol.	Inhibitory effects on survival of *Escherichia coli* and *Listeria monocytogenes*	Alvarez et al. (2013)
Okra	Alginate coating containing nanoemulsified basil (*Ocimum basilicum. L*) oil.	Effective against spoilage fungi *Penicillium chrysogenum* and *Aspergillus flavus.*	Gundewadi et al. (2018)
Carrots	Protein, polyalcohol and polysaccharide coatings.	Shelf life prolongation.	Villafañe (2017)
Green beans	Antimicrobial coating formulation consisting of modified chitosan containing a nanoemulsion of mandarin essential oil.	Reduction of L. Innocua over the storage time, owing to synergistic antimicrobial effects. A strong impact on green beans firmness.	Donsì et al. (2015)
Blueberries and raspberries	Carrageenan and green tea extract.	Antiviral activity against murine norovirus, hepatitis A virus.	Falcó et al. (2019)
Strawberries and raspberries	Alginate-oleic acid based coatings with green tea.	Antiviral effect against foodborne pathogens.	Falcó et al. (2019)
Strawberry	Prickly pear cactus mucilage (Opuntia ficus indica).	Extended shelf-life.	Del-Valle et al. (2005); Pinzon et al. (2020)
	Composite films made from banana starch-chitosan and Aloe vera gel (AV) at different concentrations.	Reduced fungal decay, increased shelf life up to 15 days during storage at 20% AV gel, while maintaining physicochemical properties (colour and firmness). Weight loss reduced 5%; limited water vapour transfer.	
Strawberry (fresh cut)	Gellan-based coatings (Gel) with Geraniol (G) and Pomegranate extract (PE) incorporation (in different concentrations).	Gel + G coatings significantly reduced microbial counts; improved microbiological stability. PE incorporation did not control microbial growth. Samples with coatings + G showed a better firmness loss than control.	Tomadoni et al. (2018)
Grape berry	Coatings based on carnauba wax-lemongrass oil nanoemulsions.	Antimicrobial effect by inhibition of *Salmonella typhimurium* and Escherichia coli. Effective at reducing weight loss, firmness, phenolic compounds, and antioxidant activity.	Kim et al. (2014)
Lime fruit	Pectin-based coating.	Progressive increase in shrivelling or wilting and loss in green colour during storage time; higher temperatures accelerated these changes.	Maftoonazad and Ramaswamy (2019)
Banana	A rice starch edible coating blended with sucrose esters.	Extended postharvest quality during ripening (at 20 ± 2 °C); effective in delaying ethylene biosynthesis and reducing respiration rate. Shelf life prolonged for 12 days.	Thakur et al. (2019),
Fuji apples (fresh cut)	Nanoemulsion-based edible coatings with lemongrass essential oil.	Inactivation of *Escherichia coli.*	Salvia-Trujillo et al. (2015)
Apple cv. Golab kohanz	Nanochitosan-based coating.	Significantly reduced weight loss, respiration rate, ethylene production and peroxidase activity; slowed down softening process and improved the flesh color after the climacteric peak.	Gardesh et al. (2016)
Papaya (fresh cut)	Psyllium gum alone and in combination with sunflower oil.	Quality maintenance and shelf life improvement.	Yousuf and Srivastava (2015)
Apricot	Chitosan coatings.	Increased content of total phenolics and antioxidant activity.	Ghasemnezhad et al. (2010)
Kiwifruit slices	*Opuntia ficus-indica* mucilage edible coating.	Significantly higher firmness and lower weight loss than untreated slices.	Allegra et al. (2017)
Cantaloupe (fresh cut)	Edible coating with antimicrobial component: chitosan, pectin, and trans-cinnamaldehyde.	Extension of shelf life to 7–9 days compared to control sample (4 days) at 4 ^{0}C. Higher concentrations (2 and 3 g/100 g) of encapsulated *trans*-cinnamaldehyde was a more effective as an antimicrobial i.e. against mesophilic microorganisms. The coating with chitosan alone was only effective against yeast and molds at a very low level.	Martiñon et al. (2014)

6.1. Fruits and vegetables

The most-wide application of edible coatings exists in the food group of fruits and vegetables in fresh or preserved forms. Most of the losses in quality of fresh fruit and vegetables occur during storage and transportation. Usually, it includes moisture loss, shrinkage, weight loss, microbial and biochemical change, mechanical damages, and sensory changes that are of common interest to be minimised or prevented. Therefore, taking into consideration that the respiratory processes of these food classes continue long after their harvest, the application of an edible packaging on fresh fruit or vegetables, will affect the gas permeability, in particular, the oxygen diffusion, and thus, inhibit the ripening processes. The products will remain fresh and attractive for an extended period, where the edible packaging acts as a barrier to free gas exchange and prevents the absorption of undesirable odours. The protection of gas exchange through edible coating can also cause modification of atmosphere around the fresh fruits/vegetable and development of anaerobic conditions that lead to alcoholic fermentation and change the sensory characteristics of packed food. Therefore, it is important to make a proper selection of edible materials for fruit and vegetable packaging to achieve an optimal balance of permeability properties. Additionally, this will result in the product keeping the moisture, appropriate adhesion to the product due to its hydrophilic nature, protecting off-flavour development, homogeneous and an attractive (i.e. glossy) appearance, keeping the fruit firm, reducing weight loss, and minimising solute leakage. In addition, these edible packaging can also encapsulate aromatic compounds, antioxidants, pigments, ions that stop browning reactions and nutritional substances (Fritz et al., 2019; Rudra et al., 2020; Yousuf & Qadri, 2020). Moreover, some examples for edible coatings applied on different fruits and vegetables include broccoli (Alvarez et al., 2013), okra (Gundewadi, Rudra, Sarkar, & Singh, 2018), carrots (Villafañe, 2017), tomatoes (Athmaselvi, Sumitha, & Revathy, 2013), cucumber (Raghav & Saini, 2018), papaya (Yousuf & Srivastava, 2015), apricot (Ghasemnezhad, Shiri, & Sanavi, 2010), kiwifruit slices (Allegra et al., 2017), fresh-cut cantaloupe (Martiñon et al., 2014), apples (Gardesh et al., 2016; Salvia-Trujillo et al., 2015), strawberry (Tomadoni et al., 2018), cherry tomatoes (Robledo et al., 2018), green beans (Donsì et al., 2015), raspberry (Falcó et al., 2019), grape (Kim et al., 2014), lime fruit (Maftoonazad & Ramaswamy, 2019), banana (Thakur et al., 2019) and others. The applications of the variety of edible packaging options for fruits and vegetables are summarised in Table 1.

6.2. Meat, poultry, fish

Meat, poultry and fish can benefit considerably from edible packaging in terms of product quality and safety, and extending their shelf life (Dong et al., 2020; Guo, Jin, Wang, Scullen, & Sommers, 2014; Pabast et al., 2018; Umaraw & Verma, 2017; Umaraw et al., 2020; Xiong et al., 2020a, 2020b). This packaging type reduces moisture loss, inhibits texture degradation, prevents unattractive dripping of product juices and consequently reduces food loss, spoilage, and waste. Furthermore, edible packaging reduces biochemical product degradation, protects lipids and proteins from oxidation, delays rancidity, and prevents undesired colour changes. Active (antimicrobial) edible materials also contribute to products' microbial safety and decrease the spoilage. Fresh meat cuts and products can be included in this category (Bhagath & Manjula, 2019; Sánchez-Ortega et al., 2014), as well as pork (Xiong et al., 2020), lamb (Pabast et al., 2018), turkey (Guo et al., 2014). A summary of these applications is presented in Table 2.

6.3. Dairy products

Relatively high rates of foodborne illness related to dairy such as human listeriosis have emphasised the importance of preventing microbial infection in dairy products. Salmonella is another bacteria that has been found in spoiled cheese (Pourmolaie, Khosrowshahi Asl, Ahmadi, Zomorodi, & Naghizadeh Raeisi, 2018). In addition, mould contamination of different dairy products such as cheese during ripening and storage is a problem for the dairy industry. Many species of aspergillus and penicillium are common fungal contaminants of the cheese (Bagheripoor et al., 2018; Cerqueira et al., 2010). The ancient solution for this problem is physically impregnating the product with spices, herbs or their oils with many studies reporting the usefulness of this form of edible packaging concept in the dairy industry, such as the study examines the cheese packaging into a chitosan-coated nisin-silica liposome with anti-listeria effects (Cui, Wu, Li, & Lin, 2016). Probiotic coating of cheeses can be an ideal vehicle for lactic acid bacteria. Namely, the *L. acidophilus* and *L. helveticus* inclusion in edible cheese coverings reduced the presence of the total coliform at ten days (Olivo et al., 2020) (Table 3).

6.4. Grains and nuts

In general, grains and nuts are products with relatively low moisture content. Edible packaging has been shown to be useful in controlling undesirable mass transfer between the products and environment. This migration from the food to the outer environment or vice-versa can decrease food quality and alter its sensory characteristics such as dehydration or spoilage, loss of aroma and flavour. In addition, edible packaging can prolong grain and nut quality by protecting from mechanical damages during transport, vibrations, and pressure as well reducing the stickiness of the grains to surfaces that they might come into contact. Active edible packaging which contains antioxidant inclusions could potentially protect the grains and nuts from lipid oxidation, for example (Arnon-Rips & Poverenov, 2016; Riveros, Mestrallet, Quiroga, Nepote, & Grosso, 2013; Sabaghi et al., 2015) (Table 3).

6.5. Baked products and candies

Edible coatings could be applied on a different baked and extruded products, such as crackers, biscuits and cereals. The loss of their crispiness and softening due to hydration during storage can be effectively managed by use of edible packaging (Jiménez et al., 2018). Edibles produced with plant essential oils (i.e. clove, oregano) displayed antimicrobial activity against the development of fungi in baked products, consequently improving shelf life (Gavahian et al., 2020; Jiménez et al., 2018; Sanguansri & Augustin, 2006). Bread, as the most consumable representative of this group, is an attractive case for application of a variety of edible coatings (Chakravartula et al., 2019; Noshirvani et al., 2017). Moreover, candies and confectioneries are an interesting and challenging group of food that can be protected from undesired stickiness, agglomeration, moisture absorption and oil migration by edible packaging (Eyiz, Tontul, & Türker, 2020). Table 3 summarizes edible packaging options for dairy, nuts and bakery products.

7. Conclusion & Future prospective

There is a tremendous interest in novel packaging solutions for a variety of food products worldwide. The emergence of new packaging technologies have enabled newly developed products to perform better than providing them with containment and physical protection. The future of edible packaging materials is very promising, and increased innovation within the food industry is both imminent and already occurring. Global consumer demands are a driving force for research and development of novel materials in order to find alternatives for fossil-based packaging materials. Their replacement with recyclable, biodegradable or edible materials, prepared from renewable and sustainable sources, are desired by consumers and the food industry alike. In this context, the use of biopolymers as food packaging possess the advantages of biodegradability, process simplicity, and an ability to be combined with other materials has a considerable potential to reduce the food waste and benefit the environment.

Table 2
Applications of edible packaging options on meat and meat products.

Food product	Edible materials	Beneficial effect	Reference
Meat and meat products			
Sliced ham	Na-alginate edible films as vehicles for delivering probiotic bacteria.	Probiotic bacteria successfully delivered in the products by edible films.	Pandhi et al. (2019); Pavli et al. (2019)
	Oregano essential oil (OEO) incorporated in Na-alginate edible films.	Reduction of *Listeria* population. Presence of OEO in the films resulted in colour differences which compared to control samples was the decrease of the product's quality, whilst the aroma of samples was improved.	
Sliced cooked ham	Film matrix composed of poly(lactic acid) containing cellulose nanocrystals (PLA-CNC); films converted to bioactive films using nisin as an antimicrobial agent.	Inhibited capacity of *Listeria monocytogenes* and their physicochemical and structural properties (stored for 14 days at 4 ^{0}C). Significant reduction of *L. Monocytogenes* in ham from day 1 and a total inhibition from day 3.	Salmieri et al. (2014)
Muscle foods	Collagen edible films.	Reduced moisture loss, minimized lipid oxidation, prevented discoloration, and reduced dripping.	Pandhi et al. (2019)
Shrimps	Bilayer films based on agar and Na-alignate with cinnamon oil.	Antioxidant activity; effective against photobacterium phosphoreum.	Arancibia et al. (2014)
Lamb meat	Nano-encapsulated Satureja khuzestanica essential oils (SKEO) in chitosan coatings (containing free or nano-encapsulated SKEO).	Effectively retarded microbial growth and chemical spoilage; encapsulation decelerated release of SKEO and led to prolonged antimicrobial and antioxidant activity; improved sensory attributes.	Pabast et al. (2018)
Turkey deli meat	Pullulan films with silver nanoparticles (Ag Nps), zinc oxide nanoparticles (ZnO NPs) oregano oil (OR) 2% and rosemary oil (RO) 2%.	Ag NPs and OR edible films were more active than ZnO NPs and RO. Ag NPs, ZnO NPs, OR, and RO based films exhibited antibacterial activity against pathogens: *Listeria monocytogenes* and *Staphylococcus aureus.*	Guo et al. (2014); Khalaf et al. (2013)
	Edible coatings incorporating chitosan, lauric arginate ester (LAE) and nisin.	Reduced Listeria innocua. Combining antimicrobial coatings or films with flash pasteurization (FP), further reduced L. Innocua.	
Roasted turkey	Four polysaccharide-based edible coatings (starch, chitosan, alginate and pectin) incorporating sodium lactate (SL) and sodium diacetate (SD) and commercial preparations Opti.Form PD4, NovaGard™ CB1, Protect-M and Guardian™ NR100.	Pectin coating treatments incorporating SL/SD, Opti.Form PD4 with or without Protect-M, and NovaGARD™ CB1 displayed higher antimicrobial efficacy against against. *L. Monocytogenes.* Frozen storage significantly enhanced the antilisterial activity of various coating treatments.	Jiang et al. (2011)
Harbin red sausage	Edible chitosan (CTS) coatings (0, 1, 2, and 3%).	Storage stability was improved with an increase in the concentration of edible CTS coating. Sustained storage stability (ph and water distribution) and inhibited microbial growth (total aerobic bacteria and lactic acid bacteria).	Dong et al. (2020)
Ham and bologna	Antimicrobial effects of carvacrol and cinnamaldehyde incorporated into apple, carrot, and hibiscus-based edible films.	Antimicrobial effect against *Listeria monocytogenes.* Carvacrol films showed better antimicrobial activity than cinnamaldehyde films. Films were more effective on ham than on bologna.	Ravishankar et al. (2012)
Fresh pork	Chitosan-gelatine edible coatings incorporating grape seed extract and/or nisin.	Effectively inhibited pork oxidation and microbial spoilage; grape seed extract further enhanced antioxidant activity against meat oxidation, but incorporating nisin into the coating did not further improve the antimicrobial and antioxidant effects.	Xiong et al. (2020)
Fresh pork loin	Oregano essential oil (OEO) and resveratrol (RES) nanoemulsion loaded in pectin (PEC) edible coating.	Significantly prolonged the shelf-life of pork by minimising the ph and colour change, retarding lipid and protein oxidation, maintaining meat tenderness, and inhibiting microbial growth.	Xiong et al. (2020)
Beef meat	Antioxidants naturally present in olives, hydroxytyrosol (HT) and 3,4-dihydroxyphenylglycol (DHPG) added to a pectin-fish gelatin edible film. A new composite film included beeswax is also compared.	Film with antioxidants reduced formation of oxidation products compared to control film without antioxidants. Suppressed lipid oxidation. Combined effect of acting as an oxygen barrier and the specific antioxidant activity of beeswax-based composite film (lipid oxidation was supressed, stored for 7 days at 4 ^{0}C).	Bermúdez-Oria et al. (2019)
Sea bass (Dicentrarchus labrax) fillets	A combination of liquid smoke and thymol encapsulated in chitosan nanofibers.	Delayed growth of total mesophilic aerobic bacteria, psychrophilic bacteria and yeast and mold during storage period.	Ceylan et al. (2018)

Several studies have incorporated known bioactive substances in edible packaging materials; the incorporation of a variety of novel functional bioactives and nutraceuticals and their controlled release from the packaging is a subject of many ongoing research studies. Usually, bioactives are encapsulated in a proper edible matrix, and the controlled released of bioactives occur under different external environments such as changes in pH, temperature, or pressure. Future research is needed to understand these concepts for novel edible packaging materials. This poses an additional challenge as these products should also be well designed, engineered and suitable for the most appropriate foods and their products. The use of nanotechnology methods allow an appropriate design of active edible films and coatings in the food industry and have the potential to offer great benefits to the safety and quality of packaged food products.

Nanotechnology can potentially enhance the nutritional value of the food by nano-scaling nutrients and nanosizing delivery systems for bioactive compounds with adjustments suitable for the particular application. Nanotechnology also has the potential to improve foods, making them tastier, healthier, and in some cases, more nutritious. This can consequently result in the generation of new food products, new food packaging, and extend storage life, all of which can rapidly contribute to reducing food waste. However, many of these applications are still at a preliminary stage with most innovation aimed at high-value products. In addition, the use of intelligent food packaging, (i.e. incorporating nanosensors in the packaging), may even provide consumers with information on the state of the food inside and potentially be used for the traceability of the food products (Chaturvedi & Dave, 2020; Raymana, Demirdövenb, & Baysala, 2016; Shafiq et al., 2020).

Human health can benefit by the usage of edible materials as packaging. In most cases, edible materials are lipids, proteins or

Table 3
Applications of edible packaging options for dairy products, nuts and bakery products.

Food product	Edible materials	Beneficial effect	Reference
Dairy products			
Cheddar cheese	Chitosan-coated nisin-silica Liposome.	Sustained antibacterial activity against *L. Monocytogenes* without affecting the sensory properties of the cheese.	Cui et al. (2016); Pourmolaie et al. (2018)
	Guar/Tragacanth gum-based edible coating.	Moisture and protein contents of the samples decreased and increased during ripening (90 days), respectively. Ph, acidity, fat in dry matter, tyrosine, and tryptophan contents of samples significantly improved with edible coatings.	
Nabulsi cheese	Chitosan- and bitter vetch protein-based films.	Wrapped unsalted cheese (WUC) maintained the pH of the fresh product during storage. Effective at hindering microorganism growth in WUC. Hardness, chewiness and gumminess of the WUC increased during storage. No effect observed at different storage times for weight loss of WUC compared to unwrapped cheese, stored both in the absence and presence of salts.	Sabbah et al. (2019)
Cheese	Edible coatings based on: sodium alginate, sodium alginate + Lactobacillus acidophilus and sodium alginate + Lactobacillus helveticus.	The *L. acidophilus* and *L. helveticus* inclusion in edible coverings reduced the total coliforms presence at 10 days. Probiotic bacteria reduced coating flexibility. *Lactobacillus helveticus* added in the cover diffuse to the cheese interior, ensuring that the cover can be a vehicle for dairy bacteria.	Olivo et al. (2020)
Nuts			
Fresh walnut kernels	Chitosan incorporating green tea extract.	Antioxidant and antifungal effects: Significant inhibition of lipid oxidation and fungal growth.	Sabaghi et al. (2015)
Roasted peanuts (RP)	Edible coatings: carboxymethyl cellulose (RP-CMC), methyl cellulose (RP-MC) and whey protein (RP-WPI).	Chemical indicator values and intensity ratings of oxidized and cardboard flavors had lower increase during storage. The stability of RP-CMC is approximatelytwice as long with respect to RP.	Riveros et al. (2013)
Bakery			
Muffins	Triticale-based edible film coating	Retard the staling process.	Pandhi et al. (2019)
Fruit bars	Edible films based on sodium alignate, carboxymethyl cellulose and whey protein isolate.	No significant effect on chemical properties. Maintained textural properties, limited moisture loss, loss of total phenolic content and radical scavenging activity during storage was prevented.	Bilbao-Sainz et al. (2018); Eyiz et al. (2020)
	Layer-by-layer electrostatic deposition of the polycation chitosan and the polyanion alginate to coat fruit bars enriched with ascorbic acid.	Increased ascorbic acid content, antioxidant capacity, firmness and fungal growth prevention during storage.	
Bakery products	Antimicrobial activity of essential oils: thyme, cinnamon, oregano, and lemongrass.	Inhibit the growth of harmful microorganisms. Extended shelf-life and enhanced safety.	Gavahian et al. (2020)
Bread (mini-burger buns)	Sodium alginate, pectin (from citrus peel), whey protein concentrate used as edible coatings.	Drying behaviour of coatings on bread surfaces.	Chakravartula et al. (2019)
Sliced wheat bread	Nanocomposite film and coating based on chitosan-carboxymethyl cellulose-oleic acid (CMC-CH-OL) incorporated with different concentrations (0.5, 1 and 2%) of zinc oxide nanoparticles (ZnO NPs)	Increased microbial shelf life from 3 to 35 days for CMC-CH-OL-ZnO NPs 2% in compared to the control. Reduced the number of yeasts and moulds over 15 days; improvement in antimicrobial properties for coatings contains 1% and 2% ZnO NPs with no fungal growth over 15 days. Better maintenance of moisture content.	Noshirvani et al. (2017)

polysaccharides alone or combined in the form of composites/blends (Fernandes et al., 2020). All are biopolymers that are compatible with humans. Moreover, additives such as nutraceuticals, bioactives, vitamins, and probiotics, enrich edible packaging and typically add active value to the packaging. Their main function in packaged food is to provide an active function such as antimicrobial, antioxidant or barrier performance. In addition, some of these constituents can promote health benefits to humans after consumption (Espitia, Batista, Azeredo, & Otoni, 2016). Furthermore, when plant extracts and oils such as thyme, clove, tea tree, rosemary oil, sea buckthorn leaves/oils, are used in food packaging, provide a healthy alternative to normal packaging due to their antimicrobial and antioxidant properties for both the food and consumers (Vasile, 2018; Zoghi, Khosravi-Darani, & Mohammadi, 2020).

Future studies should help to further develop coating technologies, and focus on optimising the formulation of packaging bio-based materials and their application technologies. The ongoing debate about the potential benefits and risks of human consumption, especially when nanoparticles are involved, are among the current challenges and also the potential to scale-up production (Liu et al., 2019; McClements & Xiao, 2017; Sampathkumar, Tan, & Loo, 2020; Sohal et al., 2018). Future developments of edible packaging solutions will also incorporate smart design packaging where novel concepts such as active, intelligent, smart and sustainable solutions are integrated into one system resulting in improved safety and quality of the packed products.

CRediT authorship contribution statement

Anka Trajkovska Petkoska: Conceptualization, Writing - original draft, Writing - review & editing, Supervision. **Davor Daniloski:** Investigation, Writing - review & editing, Visualization. **Nathan M. D'Cunha:** Writing - review & editing. **Nenad Naumovski:** Writing - review & editing. **Anita T. Broach:** Visualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

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