State of the Art on Functional Coatings for Applications in The Agri-Food Industry

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REVIEW

Abstract
Nowadays, consumer’s awareness regarding edible and functional coatings used in the food industry is increasing because of their novel approach on prolonging the shelf life of agri-food products that during storage, are subjected to a loss of quality attributes, which inevitably contributes to food waste. In order to combat this problem, functional coatings and edible films can be used because of their capability to extend the shelf life of food products by providing gas and water barrier properties and delaying microbial spoilage. The aim of this study is to review the literature and outline the most recent findings and developments regarding edible and functional coatings used in the food industry. Functional and edible coatings can be applied on different types of food products, like meat products, different kinds of cheeses and fruits and vegetables. mainly because they help maintain the organoleptic proprieties, such as aroma, taste and appearance and prologue their shelf life. The new concept of functional coatings and edible packaging has significantly influenced the marketing and safety aspects of food products and further studies and developments are needed to improve these technologies.

Keywords: edible food packaging; functions coatings; shelf-life; sustainability.

INTRODUCTION
Maintaining food safety is a known problem worldwide, affecting hundreds of millions of people suffering from contaminated food products. The World Health Organization (WHO) defines this problem as “one of the most common health problems and a major cause of declining economic productivity” (Alamri et al., 2021). Many food products are perishable and need protection against spoilage during the preparation, storage and distribution process in order to reach the desired shelf life. Consumption of food contaminated with pathogenic microorganisms is a threat to human health, with the number of people getting sick from foodborne pathogens being up to 30% of the total global population each year (Enescu et al., 2019). Packaging optimization strategies such as varying the size of packages to help buyers buy the ideal quantity, and designing packages in such a way as to maintain food quality and increase shelf life have been proposed to reduce food waste (Lopez et al., 2012; Zemljic et al., 2013). In the recent years, food packaging materials and technologies have evolved tremendously, because of the growing needs for safer food products with a longer shelf-life. In the past, food packaging was only supposed to offer physical
protection of food products, but nowadays, novel techniques like active and intelligent packaging managed to enrich the food packaging proprieties in a way that they can extend the shelf-life and safety of the packed food products (Vanderroost et al., 2014). Because of consumer health concerns and environmental issues regarding the use of plastic in the food packaging industry, new biodegradable and renewable packaging materials have been designed (Beikzadeh et al., 2020). Functional coatings and films are novel tools intended to extend the shelf-life span of food products thus playing an important role in maintaining the safety and quality attributes of the treated food products, as well in the sustainability of the environment (Villela et al., 2017).

Packaging materials like functional coatings with antimicrobial properties have to be in direct contact with the food product surface in order to be efficient. The active elements of the functional coatings can be immobilized on the surface of the packaging material but it is not allowed for them to migrate into the food product (Khaneghah et al., 2020). Functional coatings with antimicrobial properties are suitable for food products where the microorganisms are on the surface of the food product (Realini & Marcos, 2014). The antimicrobial substances present their activity by interacting directly with microorganisms retaining a substance necessary for their growth, or releasing substances into the outer space of food that inhibit microbial growth, the latter type being the most studied mechanism of action. Antimicrobial agents used as a tool to reduce food spoilage are often added directly to food. Nowadays, the use of natural antimicrobial agents like essential oils or chitosan are studied because the bioactive part of the functional coating must be a food additive thus being safe for the final consumer (Dehghani et al., 2018).

Antimicrobial substances used in functional coatings and films can be classified into three distinct groups: natural and chemical agents or bioconservatives (Khodaei et al., 2019). In terms of their action mode, antimicrobials can be classified as volatile or non-volatile. The antimicrobials used in functional coatings can be active against one or a group of microorganisms: bacteria, yeasts, molds, parasites, etc., or may be active against a single specific microorganism (Varghese et al., 2020). Antimicrobial agents can be classified as microbiostatic or microbicidal, although for many compounds it depends on the concentration (López-Cardillo et al., 2012).

Beside the antimicrobial proprieties, edible coatings and films manage to increase the firmness, titratable acidity (TA), soluble solid content (SSC) and vitamin C content for fresh cut fruits (Mahajan et al. 2014). Jongsi et al., 2016 studied the effect of a chitosan based edible film that was used to coat mango fruits, thus the treated samples presented a delayed the ripening, and better values of titratable acidity (TA), firmness and reduction in weight loss and ethylene. Tomato samples coated with solutions of algin e and chitosan presented a reduction in weight loss and ethylene levels, also firmness and color was better preserved (Salas-Méndez et al., 2019).

Also, a very important aspect is the interaction between the antimicrobial agent (essential oil) and the food matrix. A coating made of chitosan and cinnamon essential oil (0.1%) was applied on cucumber samples by Isturiz-Zapata et al., 2020, managing to inhibit microbial growth. Das et al., 2020 studied the effect of a coating made by sodium alginate and sweet orange essential oil on tomato samples, thus reducing weight loss and increasing firmness. Other applications of edible films and coating over different food matrix found in the literature are: pear samples coated with cumin essential oil (Oyom et al., 2021), strawberries coated with lemon grass essential oil (Wani et al. 2021), apple slices coated with aloe vera gel, shellac and lemon essential oil (Chauhan et al., 2011), grapes coated with peppermint essential oil (Guerra et al., 2016), meat products coated with whey protein with oregano essential oil (Catarino et al., 2017).

The spoilage of fruits and vegetables like loss of texture is caused by loss of water or microbial spoilage, the deteriorating quality of fresh meat and fish products may result in slime production, off-flavor and off-odor development, also because of microbial spoilage or other factors (Zhu, 2021).

The development of functional coatings and edible films has been a milestone in terms of extending the shelf-life of agri-food products like fruits, vegetables (Soradech et al., 2017; Aitboulahsen et al., 2018) and meat products (Jridi et al., 2018, Moreno et al., 2018).

MATERIALS AND METHODS

A literature review was performed in order to investigate new research studies that have been made in the past decade regarding emerging technologies for the functional coatings and edible films. The content analysis of the reviewed studies was aimed at defining the scope of analysis, evaluate the content and in the end to classify the content in two directions: the importance of functional coatings and edible coatings regarding the benefits brought to the food products and to the end consumer; agri-food products which have been treated with functional coatings or edible films and the results of these treatments. Web of Science, Elsevier, Wiley Online and Springer databases were electronically searched for articles published in the last decade. The literature search included several document types: research articles and reviews, on the following topics: „functional coatings”, „edible films” and „food packaging sustainability”. Sixty-eight research articles published in the last decade were gathered and synthetized from publisher databases. The vast majority of the research studies related to functional coatings and
edible films have presented studies on fruits, vegetables, meat and fish products that are coated with different formulations of functional coatings or edible films.

RESULTS AND DISCUSSIONS

Functional coatings are used in the food industry and the main forms that are present found are edible coatings and films. They are used more and more because of their advantages, such as good gas barrier attributes, being environmentally friendly, reduction of spoilage and microbial contamination and maintaining the quality and sensory attributes of the treated food products (Tavassoli-Kafrani et al., 2016). Edible films and coatings are applied by coating as thin layers or by immersion, depending on the food product (Dehghani et al., 2018). Another important aspect is the fact that they can release in time bioactive compounds (polysaccharides, carbohydrates and mucilages, proteins, and lipids) that are incorporated in them in a way that this helps extend the shelf-life of the treated food products (Gazón et al., 2017; Bahrami et al., 2020).

Various types of different functional and edible coatings have already been studied and applied to improve the shelf-life and post-harvest physiological properties of different types of food products, i.e. fruits and vegetables, strawberries (Predones et al., 2014; Riaz et al., 2020), grapes (Sánchez-González et al., 2011), fresh-cherry fruits (Arabpoor et al., 2021), carrot (Sanuja et al., 2015), broccoli (Alvarez et al., 2013); meat and fish products (Khoshhidi, Mehdizadeh, & Ghorbani, 2020; Liu & Liu, 2020; Wang et al., 2020) etc., by using dipping, spraying and other deposition methods.

Whey chitosan-protein films were made to obtain a mixture with new functionalities from the interaction of cationic polyelectrolyte chitosan with proteins. The purpose of this study was also to prepare edible films with antimicrobial properties. The antibacterial activity of the films was improved as the chitosan content of the mixture increased. The antimicrobial activity of edible chitosan films incorporated with garlic oil and nisin against E. coli, S. aureus, S. typhimurium, L. monocytogenes and B. cereus produced large areas of inhibition for S. aureus, L. monocytogenes and B. cereus. It also reduced the bacterial growth under film of E. coli and S. typhimurium (Maher & Entsar, 2013).

Starch is widely used in the development of food packaging and edible coatings because of its abundance in nature, biodegradability properties and thermoplastic forming potential (Mali et al., 2005). The properties of the films obtained from starch are suitable for use in the food industry because they are non-toxic, biodegradable, odorless, colorless and tasteless (Flores et al., 2007). Starch based edible coatings are also used in as effective coating methods in order to prologue the shelf-life of different food products. Bersaneti et al., 2021 studied the effect of a starch and nystose biodegradable film on the shelf-life of blackberry samples. The results of the study showed that the coated samples managed to maintain the pH, firmness and anthocyanin levels, without any major color changes compared to the untreated samples. Oyom et al., 2022 made a study over a coating film obtained from sweet potatoes derived starch with the active ingredient cumin essential oil. The starch-based coating was used to coat pear samples and the results showed that after 21 days of storage the respiration rate and weight loss presented better values compared to the uncoated samples. Basiak et al., 2019 developed an edible film from starch and whey protein in order to enhance the shelf-life of plum samples. The results obtained showed that the coated samples managed to lower the transpiration rate and increase the water vapor resistance.

Alehosseini et al., 2019 studied the effect of bioactive functional coatings made from electrospun protein fibers (gelatin and zein) with curcumin encapsulated in their matrix. Also, a green tea extract was incorporated in the formulation in order to evaluate its impact on the stability and release properties of the curcumin loaded fibers. Good results and encapsulation efficiencies were obtained for both protein fibers used, thus the addition of the green tea extract provided strong interactions in the proteins. The gelatin coatings presented a good release behavior when it was in contact with high fat content food products, whereas the zein-based coatings are more suitable for use in food products that have high water content.

Zhang et al., 2019 studied a novel super-hydrophobic functional coating material made from beeswax and coffee lignin. Coffee lining was used in this study because coffee beans contain a decent amount of lining, mineral and vitamins, thus the extraction of edible lignin was used to maintain micro/ nanoscale structures of coating at high temperature. Lignin is the second most found biomolecule in plants and has good structural strength. The studied showed that the coating has super hydrophobicity and good thermal stability after being heated at 120°C for 60 minutes, thus it can be applied on food packaging in which liquid foods that require high sterilization temperatures will be packed.

The current applications of functional coatings and films and coatings in various kinds of foods are summarized in Table 1.
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<th>Food products applied on</th>
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<td>Seed-based mucilage</td>
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<tr>
<td>Beeswax and coffee lignin</td>
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<tr>
<td>Gelatin-nisin/catechin + microbial transglutaminase</td>
<td>Pork meat</td>
<td>Diminished lipid oxidation by reducing barrier water/air vapor</td>
<td>Kaewprachu et al., 2018</td>
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</table>
**Functional coating for fruits and vegetables**

Fruits and vegetables are known to be very important to the human diet because of their high content of vitamins, antioxidants and minerals, but it is also known that they have a short shelf-life due to their high moisture content (Vilaplana et al., 2020). In order to prevent premature decay of these category of food products, edible coatings and films can be applied in order to control the respiration and transpiration rate, reduce the loss of water content, retain firmness and maintain color and nutritional values (Falcó et al., 2019).

Seed-based mucilage derived functional coatings and their action on different food products was reviewed by Beizkadeh et al., 2019. Based on their studies, these mucilages can be used with success in the food packaging industry because they can be extruded into films and coatings with good barrier properties against the transfer of moisture and oxygen. Also, bioactive compounds can be included in the formulation in order to stop the microbial growth and prolongue the shelf-life of the coated products. Active elements like psyllium, basil, balangu, quince, barhang, flaxseed and chitosan can be incorporated into the seed-based mucilage matrix and applied on fruits and vegetables.

Velickova et al., 2013 performed shelf-life studies on strawberries coated with edible coatings based on chitosan. The coated samples were stored at 20°C temperature and 35 - 40% relative humidity (RH). In the tests performed, four different coating formulations were used (one layer of chitosan, beeswax-chitosane-beeswax layers, three-layer coating with chitosan cross-linked with sodium tripolyphosphate, and composite layer). The effect on the strawberries samples of the edible coatings was evaluated by microbiological essay (fungal infection) as well as physico-chemical analysis (weight loss, color, firmness, pH, reducing sugars content, titratable acidity, soluble solids content and respiration rate). Also, a sensory analysis was undergone. The results showed that the three-layer samples had a decreased weight loss and senescence. The color retention and the texture of the skin was also better on the coated samples.

Speranza et al. 2018 studied the effect of a sodium alginate with L. plantarum probiotic strain edible coating on apple samples that were coated and kept for 14 days at 4°C under air or modified atmosphere storage conditions. The results showed that the functional coating managed to slow down enzymatic browning as well as maintaining the pH over the storage period.

A study made by Riaz et al., 2020 investigated the efficiency of an edible coating material made of chitosan based apple peel polyphenols and chitosan on the shelf-life of strawberries. The edible coating materials obtained were characterized by SEM, FT-IR and TGA for microstructures and thermal proprieties. The coated strawberry samples were stored in a controlled environment at 20°C and 35 - 40% RH. The analysis made were weight loss, firmness, titrable acidity (TA), and total soluble solids (TSS). The results showed that the coatings could be used in order to prolong the shelf-life of strawberries, as they slowed the senescence of the coated samples and also maintained their quality attributes during the undergone tests.

Severino et al. (2015) evaluated the antibacterial activity of modified chitosan-based coatings containing nano-emulsions of essential oils, gamma radiation, modified atmosphere packaging, alone or in combination, against *Escherichia coli* O157: H7 and *Salmonella Typhimurium*, on samples of green beans. The incorporation of carvacrol nano-emulsions into the chitosan films allowed the development of a bioactive coating that was applied to green beans samples. The results showed that the functional coatings presented antimicrobial activity against the two pathogens tested during storage.

Chitravathi et al., 2014 studied the effect of a functional coating material made of Shellac 5% (w/w), PVA 3%, oleic acid, Tween 80, starch, EDTA and sodium alginate which was used to coat green chilies. The results showed that the coated samples presented a decreased weight, and good color retention. Tomatoes coated with rice starch-based coating had lower total soluble solids compared to uncoated samples during storage (Das et al., 2013).

**Functional coating for meat products**

Srirapatrawan & Noipha, 2012 studied the incorporation of green tea extract in chitosan films, which was later used as a functional coating to extend the shelf life of pork sausages. The results obtained by the authors of the study showed that the antioxidant and antimicrobial properties of chitosan films can be improved by incorporating green tea extract into their matrix in order to extend the shelf-life of the coated food products. The active films developed could be used as active packaging to maintain the quality and extend the shelf life of chilled pork sausages.

Fernández-Saiz et al., 2013 studied the effect of chitosan films on fresh hake (*Merluccius merluccius*) and turbot (*Solea solea*) fillets in order to extend the shelf life of the coated samples. After the coating process, the fillet samples were wrapped in a film with chitosan and packed in air or vaccum. After this process the samples were put to storage for a period of 15 days, at 4-5°C. The results showed that the chitosan samples packed in air and chitosan samples packed in vaccum presented a decreased microbial load compared to the control samples. The chitosan air packaged functional coatings formulations managed to extended the shelf life of hake and turbot fillets by 7 to 9 days.
Fang et al., 2018 studied the effect of some newly developed edible films based on chitosan and gallic acid in several variants (2% chitosan and 0.2% gallic acid; 2% chitosan and 0.4% gallic acid) on pork meat samples. The results showed that the antimicrobial activity of the films increased with the addition of gallic acid. The edible films that also contained gallic acid caused lipid and myoglobin oxidation. The results showed that the meat coated had an improved shelf-life compared to the control samples (Fang et al., 2018).

A study by Lin et al., 2018 showed that a film based on chitosan and e-polylysine presented inhibitory effect against the development of two strains of Salmonella, namely *Salmonella typhimurium* and *Salmonella enteritidis* present in chicken meat. The results showed that in the control samples the number of *Salmonella typhimurium* and *Salmonella enteritidis* reached 8.21 log CFU / g and 8.37 log CFU / g when stored at 25°C, while for the coated samples with chitosan with e-polylysine film decreased to 5.03 log CFU / g and 5.25 log CFU / g. These results show that the developed chitosan films were successful in inhibiting Salmonella growth in the coated chicken samples (Lin et al., 2018).

Chang et al., 2019 studied the effect of the application of a film made of chitosan by neutralization with sodium hydroxide solution on refrigerated meat samples. The obtained results showed that the films made led to the effective protection of refrigerated meat against lipid oxidation and multiplication of microorganisms for 10 days, compared to the control sample.

Souza et al., 2019 developed bio-nanocomposites based functional coating made from chitosan and montmorillonite incorporated with rosemary essential oil, using them as packaging materials for fresh poultry meat. The samples were coated with the obtained functional coatings and stored at 5°C ± 2°C for 15 days. Following the analyzes, it was found that the packaging led to a reduction in the number of microorganisms by 1.2 - 2.1 log CFU / g, and also managed to slowdown the process of lipid oxidation and discoloration of the samples, compared to the control sample witness maintained in the same condition.

Xiong et al., 2020 studied the effect of a chitosan and gelatin functional coating incorporated with nisin and grape seed extract that was used to coat pork samples. The results showed that the functional coating inhibited lipid and protein oxidation and retarded microbial growth.

**Functional coatings for other food products**

The use of functional and edible coatings was also studied in the bakery industry. A study made by Noshirvani et al., 2017, investigated the use of a new nanocomposite coating film based on chitosan and carboxymethyl cellulose-oleic acid (CMC-CH-OL) with 0.5% concentrations was suggested, 1% and 2% of zinc oxide nanoparticles (NPn ZnO) to increase the shelf life of sliced wheat bread. The results of the antimicrobial tests showed an increase in the shelf life of sliced wheat bread from 3 to 35 days for the packaged sample in the presence of NPC film CMC-CH-OL-ZnO 2% compared to the control. All active coatings decreased the number of yeasts and molds in sliced bread for 15 days.

Lin et al., 2019 conducted a study in which they developed functional coatings based on moringa oil, chitosan nanoparticles and gelatin, for the biocontrol of two bacteria, *Listeria monocytogenes* and *Staphylococcus aureus* in cheese products. These solutions showed a high antibacterial activity on the two bacteria tested at a temperature of 4°C, respectively 25°C, for 10 days, without affecting the sensory qualities of the cheese samples.

The effect of an edible film based on chitosan and *Santolina chamaecyparissus* L. extract on 'Manchego' type cheese was carried out by Ortiz de Elguea-Culebras et al., 2019. The obtained results showed that the film applied on the product led to the increase of the antifungal and antioxidant activity on the product, compared to the control sample.

**CONCLUSIONS**

All food products are losing quality attributes such as physical (texture, color, weight loss), chemical (nutritional value, sugars, acids, pH), microbiological (yeasts, moulds, bacterial contamination) and sensory attributes (taste, color) which are very important factors for the consumer as well as the producer. These deteriorations of the quality attributes are also in close relationship to the shelf-life of different food products categories and their inherent physical and chemical proprieties. Because of these factors, the agri-food business sector and scientists in the field of food safety have tried to find novel solutions for extending the shelf-life of food products without using additives or other compounds that are unhealthy for the human diet. Functional coatings and edible films showed promising results like: extending the shelf-life and maintaining the quality attributes of the coated food products, delaying microbial spoilage and offering protection against lipid oxidation. Another important aspect of the functional coatings and films is the sustainability aspect as well as responsible consumption and production, thus by extending the shelf-life of different food products and maintaining their sensory and nutritional values for a longer period of time, making the zero-waste policy easier to be fulfilled. In 2015, the United Nations - Sustainable Development Goals set important criterias that need to be fulfilled until 2030, such as zero hunger, good health, well-being
and responsible food production, criteria which can benefit from the development of novel packaging and processing techniques such as edible and functional coatings and films.

**Author Contributions:** P.A.P and V.I.P. Conceived and designed the analysis; P.A.P and V.I.P. Collected the data; A.C.M, E.E.P and M.E.P. Contributed data or analysis tools; M.D. Performed the analysis; P.A.P. Wrote the paper.

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**Conflicts of Interest**

The authors declare that they do not have any conflict of interest.

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