BIODEGRADABLE PACKAGING AND EDIBLE COATING FOR FRESH-CUT FRUITS AND VEGETABLES

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ABSTRACT

This work focuses on biodegradable packaging and edible coatings applied to fresh-cut fruits and vegetables and their effects on the product quality. Practical applications are mainly limited to the use of biodegradable materials that, however, do not allow full control of the product moisture loss. Better results can be achieved by the combined use of biodegradable packagings with edible coatings and recent research has shown that enrichment with silver-montmorillonite nanoparticles may be a promising technique. However, the actual utilization of these materials is still limited, due to the high costs of the raw materials and the limited production.

- Keywords: biodegradable packaging, biopolymers, edible coating, fresh-cut fruits and vegetables, minimally processed foods, nanocomposites -

INTRODUCTION

In recent years, the establishment of new lifestyles, characterized by a lack of time in domestic preparations, has been accompanied by an evolution of the structure of food consumption and a destructuring of meals. Therefore, the consumption of minimally processed fruits and vegetables has grown rapidly as a result of the consumer trend- "rich in cash, poor in time" (MARTÍN-DIANA *et al.*, 2007; CONTE *et al.*, 2009).

Minimally processed fruits and vegetables were developed in the 1980s to respond to the emerging consumer demand for both convenience and high quality aspects (DEL NOBILE *et al.*, 2008). These foodstuffs combine fresh-like and healthy characteristics with a minimal time of preparation before consumption (RAGAERT *et al.*, 2004). In fact, their success is also due to the beneficial health effects for the presence of antioxidants that act as receptors of free radicals; in particular, ascorbic acid and β-carotene are the antioxidants present in the greatest quantities in fruits and vegetables (RICO *et al.*, 2007).

The minimal processing operations ("mild technology") necessary to produce fresh-cut foods, such as peeling, cutting, washing, treatments with sanitizing agents, drying, alter the physical integrity of these products, making them more perishable than the original raw materials (CORBO *et al.*, 2006). This is due to respiration, transpiration, enzymatic activity of the living tissue after harvest and processing and, at the same time, to proliferation of spoilage and pathogenic microorganisms (GALGANO *et al.*, 2014; NGUYEN-THE and CARLIN, 1994). The industrial process accelerates the degradation of the minimally processed foods and leads to biochemical changes such as:

- increasing of respiration that accelerates the oxidation processes;
- degradation of cell membranes and enzymatic browning;
- loss of tissue texture.

The knowledge of factors influencing quality degradation after processing of fruits and vegetables is essential to develop technologies for shelf-life extending and maintaining quality during processing and distribution (CORBO *et al.*, 2006).

In order to reduce the microbiological, chemical and physical spoilage, it is possible to act on processing or, more usually, on packaging that represents a barrier to qualitative decay of the product (GALGANO *et al.*, 2014). The packaging operation should establish inside the packaging an optimal atmosphere for the best preservation of the product. Generally, low O_2 and elevated CO_2 atmospheres, associated with low storage temperature, reduce product respiration rate, limiting, in this way, losses in fresh weight (WATADA *et al.*, 1996). Therefore, a proper combination of product characteristics and film permeability results in the evolution of an appropriate atmosphere within packages (SMITH *et al.*, 1987).

Traditionally, food companies use polymeric films (polyethylene PE, polypropylene PP, polystyrene, PS) to package fresh fruits and vegetables because of their large availability at relatively low cost and their good mechanical performance, good barrier to oxygen, carbon dioxide (SIRACUSA *et al.*, 2008). Nowadays, there is a growing trend in fresh fruits and vegetables packaging sector to replace the petrochemical based packaging films with more environmentally-friendly biodegradable materials (THARANATHAN, 2003). The extensive use of synthetic packaging films has led to serious ecological problems due to their total non- biodegradability. Therefore, biodegradability is not only a functional requirement but also an important environmental attribute. Biologically-based packaging contains raw materials originated from agricultural sources, produced from renewable raw materials such as starch and bio-derived monomers (LUCERA *et al.*, 2010). These materials represent a viable alternative because:

- they are obtained from renewable sources;
- they are recyclable and degradable;
- they are an opportunity to reduce costs.

The applications range from the design of multilayer barrier *coating* consisting of biopolymers, to enrichment of the matrix of traditional plastics PP and PE with nanocomposite materials of natural origin. However, bio-packaging still represents a niche market because of the cost and poor overall performance of biodegradable films when compared to those of traditional plastic materials (DEL NOBILE *et al.*, 2009 a).

The present work focuses on the different packaging strategies for fresh-cut fruits and vegetables. In particular, the potential applications of biodegradable materials and edible coatings have been described, with their effects on the quality of these products. The application of nanotechnology, as a tool to improve the performance and thermal, barrier and mechanical properties of bio-polymers has also been assessed (AZEREDO, 2009).

BIO-BASED MATERIALS FOR FOOD PACKAGING

The term "*Bio-Based Materials*" *(BBM)* is assigned to packaging materials and to packaging produced from biological renewable raw materials (PIERGIOVANNI and MASCHERONI, 2007).

Polymers derived from renewable resources (biopolymers) are broadly classified according to method of production, as follows:

1. Polymers directly extracted/removed from natural materials (mainly plants). Examples are polysaccharides, such as starch and cellulose and proteins, like casein and wheat gluten, and lipids.

2. Polymers produced by "classical" chemical synthesis from renewable bio-derived monomers. A good example is polylactate, a biopolyester polymerised from lactic acid monomers. The monomer itself is produced via fermentation of carbohydrate feedstock.

3. Polymers produced by microorganisms or genetically transformed bacteria. The best known bio-polymer types are the polyhydroxyalkanoates, mainly polyhydroxy butyrates and copolymers of hydroxy-butyrate (HB) and hydroxyvalerate (HV) (PETERSEN *et al.,* 1999).

The compostability attribute is very important for biopolymer materials, because composting allows disposal of the packages in the soil, which is more energy efficient than recycling. During biological degradation water, carbon dioxide and inorganic compounds without toxic residues are produced.

According to the European Bioplastics, biopolymers made with renewable resources have to be biodegradable and especially compostable, so they can act as fertilizers and soil conditioners. Whereas plastics based on renewable resources must not necessarily be biodegradable or compostable, the bioplastic materials do not necessarily have to be based on renewable materials, because the biodegradability is directly correlated to the chemical structure of the materials rather than the origin. In particular, the type of chemical bond defines whether and in what time the microbes can biodegrade the material. Several synthetic polymers are biodegradable and compostable, such as starch, cellulose, which are naturally carbon-based polymers. Viceversa, the bioplastics based on natural monomer, can lose their biodegradability through chemical modification like polymerization, such as for example Nylon 9 type polymers obtained from polymerization of oleic acid monomer or Polyamid 11 obtained from the polymerization of castor oil monomer (SIRACUSA *et al.,* 2008).

The problems associated with renewable biopolymers are threefold: performance, processing and cost. Although these factors are somewhat interrelated, problems due to "performance and processing" are more pronounced with polymers extracted directly from biomass (cellulose, starch, proteins). Conversely, polymers belonging to categories 2 and 3 above, generally perform very well and are easily processed into films using standard plastic techniques, but tend to be expensive compared with synthetic analogues (PETERSEN *et al.,* 1999).

Polymers directly extracted/removed from natural materials

Polysaccharides

The polysaccharides show effective gas barrier properties although they are highly hydrophilic and show high water vapor permeability in comparison with commercial plastic films. The main polysaccharides that can be included in edible coating formulations are starch and starch derivates, cellulose derivates, alginate, carrageenan, chitosan, pectin, and several gums. Based on the molecular level, polysaccharides vary according to their molecular weight, degree of branching, conformation, electrical charge and hydrophobicity. Variations in these molecular characteristics will lead to variations in the ability of different polysaccharides to form coatings, as well as to variations in the physicochemical properties and performance of the coatings formed. For example, the linear structure of some of these polysaccharides such as cellulose, amylose (a component of starch), and chitosan makes their films tough, flexible, transparent, and resistant to fats and oils (VARGAS *et al.,* 2008).

Starch, a storage polysaccharide of cereals and legumes, is most commonly used in the formulation of edible coatings and films because it is inexpensive, abundant, biodegradable, and easy to use. Films based on starch have moderate gas barrier properties. Their mechanical properties are generally inferior to synthetic polymer films. When a plasticizer, such as water, is added starches exhibit thermoplastic behavior (KROCHTA and MULDER-JOHNSTON, 1997). Starch-based thermoplastic materials have been commercialized over the last few years and today dominate the market of bio-based, compostable materials (CLAUS, 2000). The properties of the starch-based materials can be improved by destructuring the native conformation of the starch and adding synthetic substances. It is common practice to add copious amounts of synthetic polymer to the starch, such as polyvinyl alcohol (PVA) or polycaprolactone.

Another important polysaccharide is chitosan, which is mainly obtained from crab and shrimp shells (HIRANO, 1999). Films and coatings based on chitosan have selective permeability to gases (CO_2 and O_2) and good mechanical properties. However, their uses are limited mainly because of their high water vapor permeability (BUTLER *et al.*, 1996; CANER *et al.*, 1998). Moreover, chitosan shows antifungal and antibacterial properties, which are believed to have originated from its polycationic nature. An edible film with innovative characteristics has been obtained by combining the antimicrobial properties of chitosan with the property of self-sealing banana starch, variety Kluai Namwa. The presence of starch in the composite film makes water soluble and sealable bags or wraps possible, while the presence of chitosan gives them the antimicrobial property. The composite bags were found to protect asparagus, baby corn and Chinese cabbage against *Staphylococcus aureus* activity by serving as a good barrier and as an antimicrobial agent. The properties of composite films were more similar to starch films than to films made solely from chitosan as the amount of banana flour was greater than chitosan in the films. These composite films were cheaper and less flexible than chitosan films. Film extensibility was improved by the addition of banana flour and glycerol. Banana flour addition enhanced WVP and solubility, although, the films were not completely smooth. The biodegradable and hot water soluble films can be used in food packaging and to reduce microbial counts thus extending shelf-life of fruit and vegetables in convenient bags (PITAK and RAKSHIT, 2011).

Cellulose is the most abundant natural polymer on earth and it is an essentially linear polymer of anhydroglucose. As a consequence of its chemical structure, it is highly crystalline, fibrous, and insoluble. Many derivatives of cellulose have excellent properties of film-forming, but are simply too expensive for use on a large scale. Finally, the similarity of cellulose and chitosan in primary structures has facilitated the formation of homogeneous composite films. MÖLLER *et al.* (2004) reported that 1% of chitosan in chitosan-HPMC (hydroxypropylmethylcellulose) composite films is effective against *L. monocytogenes*.

Alginates can also be used to prepare edible coatings and films. Alginates are the salts of alginic acid, which is a linear copolymer of D-mannuronic and L-guluronic acid monomers. Alginate coating formation is based on the ability of alginates to react with di-valent and tri-valent cations such as calcium, ferrum or magnesium, which are added as gelling agents (CHA and CHINNAN, 2004). An original study (NORAJIT *et al.*, 2010) investigated the physical and antioxidant properties of alginate biodegradable film incorporating white, red and extruded white ginseng extracts. The major pharmacologically active constituents of ginseng are triterpene saponins called ginsenosides. The studies demonstrate that the ginseng extract can be successfully incorporated into biodegradable alginate films and retain excellent antioxidant activities. The incorporation of ginseng extract into the alginate films did not cause major changes in the moisture content values. On the other hand, significant reductions in tensile strength and elastic modulus values of ginseng-alginate film have been found compared to those of the film without ginseng extract.

Galactomannans, natural polysaccharides commonly used in the food industry, mostly as a stabilizer, thickener and emulsifier, are one of the alternative materials that can be used for the production of edible films/coatings based on their edibility and biodegradability. These gums are mostly obtained from the endosperm of dicotyledonous seeds of numerous plants, particularly the *Leguminosae*. The great advantage of galactomannans is their ability to form very viscous solutions at relatively low concentrations that are only slightly affected by pH, ionic strength and heat processing. The mechanical, barrier and rheological properties of galactomannan films/coatings may be used to improve the stability, safety, and quality of food products (CERQUEIRA *et al.*, 2011). LIMA *et al.* (2010) successfully blended collagen with two galactomannans from different species (*A. pavonina and C. pulcherrima*). The composition of films/coatings with different proportions of galactomannan, collagen and glycerol have been optimized based on the wettability of films, transport and mechanical properties; these films have been subsequently used to coat mangoes and apples. The results showed that the application of the coatings leads to a decrease of gas transfer rates of the fruits. For mangoes, a coating of *A. pavonina* galactomannan (0.5%), collagen (1.5%) and glycerol (1.5%) decreased oxygen consumption and carbon dioxide production in 28% and 11%, respectively. For apple, the oxygen consumption and carbon dioxide production decreased for both gases by approximately 50%, with the utilization of a coating of *C. pulcherrima* galactomannan (0.5%) and collagen (1.5%).

Proteins

Proteins that have received great attention for their capability of forming edible films and coatings include corn zein, wheat gluten (WG), soy protein, whey protein, casein, collagen/gelatin, pea protein, rice bran protein, cottonseed protein, peanut protein, and keratin (HAN and GENNADIOS, 2005). Casein based edible coatings are attractive for food applications due to their high nutritional quality, excellent sensory properties, and strong potential for providing food products with adequate protection against their surrounding environment. Whey proteins have been subjected to intense investigation over the past decade or so. With the addition of plasticizer, heat-denatured whey proteins produce transparent and flexible water-based edible coatings with excellent oxygen, aroma, and oil barrier properties at low relative humidity. However, the hydrophilic nature of whey protein coatings causes them to be less effective as moisture barriers (VARGAS *et al.*, 2008). The water vapor permeability limits their potential uses for food packaging and justifies the interest in natural hydrophobic substances, such as lipids.

Lipids

Edible lipids used to develop edible coatings are: beeswax, candelilla wax, carnauba wax, triglycerides, acetylated monoglycerides, fatty acids, fatty alcohols, and sucrose fatty acid esters. Lipid coatings and films are mainly used for their hydrophobic properties, representing a good barrier to moisture loss. This factor is extremely important, as a great number of studies deal with the use of coatings on fresh fruits and vegetables to control their desiccation. In addition to preventing water loss, lipid-based coatings have been used to reduce respiration, thereby extending shelf life and to improve appearance by generating a shine on fruits and vegetables. In contrast, the hydrophobic characteristic of lipids forms thicker and more brittle films. Consequently, they must be associated with film forming agents such as proteins or cellulose derivatives (DEBEAUFORT *et al.*, 1993).

Polymers produced by "classical" chemical synthesis from renewable bio-derived monomers

Aliphatic polyesters belong to this category and are obtained from bio-derived monomers by means of classical polymerization procedures. One of the most promising biopolymer is the poly(lactic acid) (PLA), which is derived from the controlled depolymerization of the lactic acid monomer, obtained from the fermentation of sugar feedstock, corn, etc., which are renewable resources readily biodegradable (CABEDO *et al.*, 2006). Discovered in 1932 by CAROTHERS (JAMSHIDIAN *et al.*, 2010), it is a versatile polymer, recyclable and compostable, with high transparency, high molecular weight, good processability and water solubility resistance. In comparison to other biopolymers, the production of PLA has numerous advantages including:

a) production of the lactide monomer from lactic acid, which is produced by fermentation of a renewable agricultural source corn (usually based on the strain of *Lactobacillus*);

b) fixation of significant quantities of carbon dioxide via corn (maize) production by the corn plant;

c) significant energy savings;

d) the ability to recycle back to lactic acid by hydrolysis or alcoholysis;

e) the ability to tailor physical properties through material modification (DORGAN *et al.*, 2000).

PLA is generally recognized as safe (GRAS) by the United State Food and Drug Administration (FDA). Moreover, PLA can be easily processed by conventional processing techniques used for thermoplastics like injection moulding, blow moulding, thermoforming and extrusion. PLA can be used in a wide range of applications; the major PLA application today regards packaging (nearly 70%). PLA food packaging applications are ideal for fresh products, such as fresh meat (GALGANO *et al.*, 2009) or fruits and vegetables.

Polymers produced by microorganisms: polyhydroxyalkanoates (PHA)

In recent years poly-β-hydroxyalkanoates (PHA) have attracted a lot of attention as biocompatible and biodegradable thermoplastic materials with potential applications.

Poly(3-hydroxybutyrate) (PHB) is one of the well-known biodegradable poly(hydroxy alkanoates) (PHA). PHB is a natural thermoplastic polyester and has many mechanical properties comparable to synthetically produced degradable polyesters such as the poly-L-lactides (FREIER *et al.*, 2002). Since 1925 PHB has been produced by bacterial fermentation (ROSA *et al.*, 2004), which takes place in the presence of a wide variety of bacteria, as intracellular reserve material. At least 75 different genera of bacteria have been known to accumulate PHB as intracellular granules. This polymer is synthesized under limited culture conditions and its production has most commonly been studied with microorganisms belonging to the genera *Alcaligenes, Azobacter, Bacillus and, Pseudomonas* (UGUR *et al.*, 2002). PHB films are degraded by numerous microorganisms (bacteria, fungi and algae) in various ecosystems. When in contact with the polymer, the microorganisms secrete enzymes that break it into successively smaller segments, thereby reducing the average molecular weight (BUCCI *et al.*, 2005). These polymers, alone or in combination with synthetic plastic or starch produce excellent packaging films. The polyalkanoates are more hydrophobic than the polysaccharide-based materials, resulting in a material with good moisture barrier properties, whereas the gas barriers are inferior (PETERSEN *et al.*, 1999). PHB has been used in small disposable products and in packing materials. However, little is known about the application of PHB to packaging for food products. This polymer is not used in cut-fruits and vegetables, so there is no sense to have it here, unless you write some possible uses in cut-fruits and vegetables.

Another biopolymer produced from microorganisms is the pullulan, extracted from cells of *Aureobasidium pullulans, Tremella mesenterica* and *Cyttaria harioti.* It is characterized by high resistance to fats, good barrier to gases; moreover, it is completely biodegradable and can be processed with conventional techniques. Chemically pullulan is a polymer of maltotriose used in combination with sorbitol and fatty acids esterified with sucrose to achieve edible coatings for fruits (PIERGIOVANNI and MASCHERONI, 2007). In a recent study the possibility of using new biodegradable material such as kefiran, a microbial polysaccharide obtained from the flora of kefir grains has been investigated (GHASEMLOU *et al.*, 2011). It is a water-soluble polysaccharide containing approximately equal amounts of glucose and galactose (MICHELI *et al.*, 1999), used in the food industry as a texturing agent and gelling agent. It could be a viable alternative to synthetic materials for food packaging, also because it has antibacterial and anticancer properties (MAEDA *et al.*, 2004).

The biopolymers fulfill environmental requirements, but show some limitations in terms of performance, such as thermal resistance, mechanical properties and barrier properties, associated with high costs. So, more research needs to be carried out on the packaging material with a view to introducing, for instance, intelligent molecules or inorganic material, preferably in the form of nano-particles, in order to expand the range of properties of the materials. The protagonist of the twenty-first century is another scientific innovation that is affecting the packaging industry: *nanotechnology.*

NANOTECHNOLOGY AND NANOCOMPOSITES

The concept of nanotechnology was introduced by RICHARD FEYMAN in 1959 at a meeting of the American Physical Society (KHADEMHOSSEINI and LANGER, 2006). Nanotechnology is defined as "The design, characterization, production and application of structures, devices and systems by controlling the shape and size at the nanometer scale" (Royal Society and Royal Academy of Engineering, Nanoscience and Nanotechnologies, 2004). Nanotechnology and its application in food science have recently been studied by several researchers. The use of nanoparticles, such as micelles, liposomes, nanoemulsions, biopolymeric nanoparticles aimed at ensuring food safety, are some novel nano-food applications. Nanotechnology is also applicable in the context of food packaging: however, the use of edible and biodegradable polymers has been limited because of problems related to performance (such as brittleness, poor gas and moisture barrier), processing (such as low heat distortion temperature), and cost. The application of nanotechnology to these polymers may open new possibilities for improving not only the properties but also the cost-price-efficiency (SORRENTINO *et al.,* 2007). The use of fillers with at least one nanoscale dimension (nanoparticles) produces nanocomposites. Most reinforced materials present poor matrix–filler interactions, which tend to improve with decreasing filler dimensions. Nanoparticles have proportionally a larger surface area than their microscale counterparts, which favors the filler–matrix interactions and the performance of the resulting material.

Polymer composites are mixtures of polymers with inorganic or organic fillers with certain geometries (fibers, flakes, spheres, particulates). A uniform dispersion of nanoparticles leads to a very large matrix/filler interfacial area, which changes the molecular mobility, the relaxation behavior and the consequent thermal and mechanical properties of the material. Although several nanoparticles have been recognized as possible additives to enhance polymer performance, the packaging industry has focused its attention mainly on layered inorganic solid like clay and silicates, due to their availability, low cost and relative simple processability (AZEREDO, 2009). The most widely studied type of clay fillers is montmorillonite (MMT), a hydrated alumina-silicate layered clay consisting of an edge-shared octahedral sheet of aluminum hydroxide between two silica tetrahedral layers (WEISS *et al.,* 2006). MMT is an effective reinforcement filler, due to its high surface area and large aspect ratio (50–1000) (UYAMA *et al.,* 2003). Furthermore, the presence of this nanoclay in polymer matrix increases its degradation rate, due to hydroxyl groups of MMT (SOUZA *et al.*, 2013).

MANGIACAPRA *et al.* (2005) reported that it is possible to reduce the oxygen permeability by adding clay montmorillonite to pectins. Also the combination of PLA film with MMT-layered silicates may be useful to create a nanocomposite material with good barrier properties (SOUZA *et al.*, 2013).

Moreover, a starch/clay nanocomposite film have been obtained by dispersing MMT nanoparticles via polymer melt processing techniques (AVELLA *et al.,* 2005). The results related to mechanical characterization showed an increase of modulus and tensile strength.

Besides nano-reinforcements, nanoparticles can have other functions when added to a polymer, such as antimicrobial activity, enzyme immobilization, biosensing (AZEREDO, 2009). The incorporation of antimicrobial compounds into food packaging materials has received considerable attention. Films with antimicrobial activity could help control the growth of pathogenic and spoilage microorganisms. An antimicrobial nanocomposite film is particularly desirable due to its acceptable structural integrity and barrier properties imparted by the nanocomposite matrix, and the antimicrobial properties contributed by the natural antimicrobial agents impregnated within (RHIM and NG, 2007). The most common nanocomposites used as antimicrobial films for food packaging are based on silver, which is well known for its strong toxicity towards a wide range of microorganisms (LIAU *et al.*, 1997), with high temperature stability and low volatility (KUMAR and MÜNSTEDT, 2005). Some mechanisms have been proposed for the antimicrobial property of silver nanoparticles (Ag-NPs): adhesion to the cell surface, degrading lipopolysaccharides and forming "pits" in the membranes, largely increasing permeability (SONDI and SALOPEK-SONDI, 2004); penetration inside bacterial cell, damaging DNA (LI *et al.,* 2008); and releasing antimicrobial Ag^{+} ions by Ag-NPs dissolution (MORONES *et al.*, 2005). Moreover, Ag-NPs absorbs and decomposes ethylene (HU and FU, 2003), which may contribute to its effects on extending shelf life of fruits and vegetables. Indeed, LI *et al.* (2009) reported that a nanocomposite PE film with Ag-NPs can retard the senescence of jujube, a Chinese fruit. AN *et al.* (2008) reported that a coating containing Ag-NPs is effective in decreasing microbial growth and increasing shelf life of asparagus.

The three new requirements of food packaging are the following: "Bioactive, Biodegradable and Bionanocomposite". However, there are many safety concerns about nanomaterials, as their size may allow them to penetrate into cells and eventually remain in the system. One can assume that the application of nanoparticles with an antimicrobial function (the nanoparticles of silver or copper) poses the risk the consumer's direct exposure to metals. Although the migration of metals from biodegradable nanocomposite film of starch / clay applied to vegetable products is considered to be minimal (AVELLA *et al.*, 2005), it is necessary to have more accurate information about the likely impact on human health. In fact, many studies and experiments relating to the use of nanoparticles are still in progress in order to avoid premature generalizations that could undermine the potential benefits obtainable from this technology. In the next section, the potential applications of this new category of materials (biodegradable, edible coating and nanocomposites) and their possible effects on the quality characteristics of fresh-cut fruit and vegetables is discussed.

EDIBLE FILMS AND COATINGS FOR FRESH-CUT FRUITS AND VEGETABLES

Consumers usually judge the quality of fresh-cut fruit on the basis of appearance and freshness at the time of purchase (KADER, 2002). However, minimal processing operations alter the integrity of fruits, with negative effects on product quality, such as browning, off-flavour development and texture breakdown. Also, the presence of microorganisms on the fruit surface may compromise the safety of fresh-cut fruit.

Traditionally, edible coatings have been used in the fresh-cut industry as a strategy to reduce the deleterious effects that minimal processing imposes on intact vegetable tissues.

An edible coating may be defined as a thin layer of material that covers the surface of the food and can be eaten as part of the whole product. Therefore, the composition of edible coatings must be conform to the regulation that apply to the food product concerned (GUILBERT *et al.*, 1995; VARGAS *et al.*, 2008).

Edible coatings may contribute to extend the shelf-life of fresh-cut fruits by reducing moisture and solute migration, gas exchange, respiration and oxidative reaction rates, as well as by reducing or even suppressing physiological disorders (BALDWIN *et al.*, 1996; PARK, 1999). Edible coatings are capable of producing a modified atmosphere on coated fruits by isolating the coated product from the environment. Coatings with selective permeability to gases are capable of decreasing the interchange of O_2 and CO_2 between coated fruits and the environment (OLIVAS and BARBOSA-CÁNOVAS, 2005). High CO_2 concentration within fruit tissues also delays ripening by decreasing the synthesis of ethylene, a hormone essential for ripening (SALTVEIT, 2003). LEE *et al.* (2003) demonstrated that the respiration rate of apple slices decreases 20% when coated with a film based on whey protein. Edible coating based on aloe vera reduced respiration rate and microbial spoilage in sliced kiwifruit (BENÍTEZ *et al.*, 2013). Fresh-cut products are characterized by high water transpiration rates and the creation of a moisture and gas barrier may lead to weight loss and respiration rate reduction, with a consequent general delay of produce senescence (VALENCIA-CHAMORRO *et al.*, 2011). Coating apple slices with a carbohydrate/lipid bilayer film reduces water loss during storage between 12 to 14 times when compared to the water loss suffered by uncoated apple slices in similar storage conditions (WONG *et al.*, 1994). Alginate coatings prevented water loss on fresh-cut apple (LEE *et al.*, 2003; FONTES *et al.*, 2007), papaya (TAPIA *et al.*, 2007), pear (OMS-OLIU *et al.*, 2008a), and melon (OMS-OLIU *et al.*, 2008b). Chitosan coatings reduced water loss in sliced mango (CHIEN *et al.*, 2007) and carrageenan coatings prevented water loss on sliced banana (BICO *et al.*, 2009). The cassava starch edible coating with or without the calcium lactate was able to reduce weight loss in fresh-cut pineapple (BIERHALS *et al.*, 2011), while the cassava starch edible coating with or without potassium sorbate decreased the respiration rate in fresh-cut strawberries (GARCIA *et al.*, 2010). Minimally processed pummelo (*Citrus Maxima* Merr.), coated with starch-based coatings (derived from cassava and rice) had a lower weight loss of 4.8–7.7% compared to the control (non-coated minimally processed pummelo) (KERDCHOECHUEN *et al.*, 2011). Moreover, the combination of citric acid dipping and cassava starch or sodium alginate edible coatings was able to delay the quality deterioration of fresh-cut mangoes, decreasing the respiration rate of fruits with value up to 41% lower than the control fruit. Although the citric acid increases the weight loss of the product, causing a partial dehydration of the vegetable tissue, the use of cassava starch and alginate coatings was able to hinder this undesirable effect of citric acid, presenting a lower weight loss than the coated samples (CHIUMARELLI *et al.*, 2011). In a previous work, CHIUMMARELLI *et al.* (2010) reported that this treatment provided a better maintenance of colour characteristics, due to the combined effect of citric acid dipping and cassava starch coating. Citric acid delayed browning along the storage and the edible coatings acted as a gas barrier, decreasing the respiration rate of mango pieces and, consequently the formation of carotenoids.

Moreover, another important advantage of edible coating is the reduction of synthetic packaging waste, because these coatings are composed of biodegradable raw material (DHALL, 2013).

The properties of edible coating depend primarily on molecular structure rather than molecular size and chemical constitution. Specific requirements for edible films and coatings are as follows (ARVANITOYANNIS and GORRIS, 1999):

- the coating should be water-resistant so that it remains intact and covers a product adequately, when applied;
- it should not deplete oxygen or build up excessive carbon dioxide. A minimum of 1–3% oxygen is required around a commodity to avoid a shift from aerobic to anaerobic respiration;
- it should reduce water vapor permeability;
- it should melt above 40°C without decomposition;
- it should be easily emulsifiable, non-sticky or should not be tacky, and have efficient drying performance;
- it should never interfere with the quality of fresh fruit or vegetable and not impart undesirable order;
- it should have low viscosity and be economical;
- it should be translucent to opaque but not like glass and capable of tolerating slight pressure.

The ability of edible coatings to preserve the quality of fresh-cut products may vary from product to product, then it is necessary to consider the variety and maturity of the product, food surface coverage, storage conditions and composition and thickness of the coating (GONZÁLEZ-AGUILAR *et al.*, 2010).

According to their components, edible films and coatings can be divided into three categories: hydrocolloids, lipids, and composites. Hydrocolloids include proteins and polysaccharides, while lipids include waxes, acylglycerols, and fatty acids. Composites contain both hydrocolloid components and lipids. Their presence and abundance determine the barrier properties of material with regard to water vapor, oxygen, carbon dioxide, and lipid transfer in food systems. However, none of the three constituents can provide the needed protection by themselves and so are usually used in a combination for best results (MCHUGH *et al.*,1994; GUILBERT *et al.,* 1996). The main objective of producing composite films is to improve the permeability or mechanical properties according to specific applications. These heterogeneous films are applied either in the form of an emulsion, suspension, or dispersion of the non miscible constituents, or in successive layers (multilayer coating or films), or in the form of a solution in a common solvent. Several other compounds such as plasticizers and emulsifiers may be added to edible films and coatings to improve their mechanical properties and form stable emulsions when lipids and hydrocolloids are combined (VALENCIA-CHAMORRO *et al.,* 2011). The application of edible coatings to fresh-cut fruits must address the problem regarding the difficult adhesion of materials to the hydrophilic surface of the sliced fruit. The layer-by-layer (LbL) electrodeposition can solve this problem (WEISS et al., 2006). LbL assembly, which is performed by alternating the immersion of substrates in solutions of oppositely charged polyelectrolytes with rinsing steps, produces ultrathin polyelectrolyte multilayers on charged surfaces. A requirement for multilayer formation is that the addition of an opposite charged polyelectrolyte to a charged surface results in a charge reversal, which permits the successive deposition of oppositely charge polyelectrolytes. Chitosan, poly-L-lysine, pectin, and alginate are the most common biopolymers that can be used in the formation of these multilayered structures (MARUDOVA *et al.*, 2005; KRZEMISKI *et al.*, 2006; BERNABÉ *et al.*, 2005). In a study of MANTILLA *et al.* (2013), an alginate-based multilayered coating (developed using the layer-by-layer technique) enhanced the quality and shelf-life of fresh-cut pineapple extending its shelf-life to 15 days at 4°C.

The main advantage of using edible films and coatings is that several active ingredients (such as antimicrobials, antibrownings, texture enhancer and nutraceuticals) can be incorporated into the polymer matrix and consumed with the food, thus enhancing safety or even nutritional and sensory attributes (ROJAS-GRAÜ *et al.,* 2009).

Antimicrobial agents

Fresh-cut fruits are more perishable than their corresponding whole uncut commodities due to wounding during preparation (BRECHT, 1995). The physical and chemical barrier provided by the epidermis, which prevents the development of microbes on the fruit surface, is removed during processing.

There are several categories of antimicrobials that can be potentially incorporated into edible films and coatings, including organic acids (acetic, benzoic, lactic, propionic, sorbic), fatty acid esters (glyceryl monolaurate), polypeptides (lysozyme, peroxidase, lactoferrin, nisin). ESWARANANDAM *et al.* (2006) incorporated malic and lactic acid into soy protein coatings aiming to evaluate its effect on the sensory quality of fresh-cut cantaloupe melon, without studying the antimicrobial effect of the coating. In general, organic acids incorporated in films did not adversely affect the sensory properties of coated fruit.

With reference to the use of natural antimicrobials, the development of coatings which use inherently antimicrobial polymers as a support matrix is very promising. For example, chitosan, produced from the deacetylation of crustacean chitin (poly-β-(1→4)-N-acetyl-D-glucosamine), is one of the most effective antimicrobial film forming biopolymers. Chitosan is a cationic polysaccharide, which, among other antimicrobial mechanisms, promotes cell adhesion by the interaction of the positive-charged amines with the negative charges in the cell membranes, causing leakage of intracellular constituents (HELANDER *et al.*, 2001). Chitosan based coatings were shown to protect highly perishable fruits like strawberries, raspberries, grapes and fresh-cut-green pepper from fungal decay. (VARGAS *et al.*, 2006; EL GAOUTH *et al.*, 1991; ZHANG and QUANTICK, 1998; ROMANAZZI *et al.*, 2002; DEVLIEGHERE *et al.*, 2004; PARK *et al.*, 2005, RAYMOND *et al.*, 2012).

The application of chitosan edible coating on fresh-cut broccoli (MOREIRA *et al.*, 2011a) significantly reduced mesophilic and psychrotrophic counts and inhibited the growth of total coliform with respect to the control samples, throughout the whole storage period. Similar results were reported by GERALDINE *et al.* (2008) working with minimally processed garlic. At the end of the storage, yeasts and molds were the most dominant flora and represented the largest part of the total aerobic count in broccoli. On the contrary, DURANGO *et al.* (2006) founded an important fungicidal action of chitosan applied on minimally processed carrot. Moreover, the application of mild heat shock enhanced the chitosan inhibition action (MOREIRA *et al.*, 2011b). From a sensory point of view, the chitosan inhibited the yellowing and opening florets of fresh-cut broccoli. Moreover, chitosan-based edible coatings can also be used to carry other antimicrobial compounds such as organic acids (OUTTARA *et al.*, 2000), essential oils (ZIVANOVIC *et al.*, 2005), spice extracts (PRANOTO *et al.*, 2005), lysozyme (PARK *et al.*, 2004) and nisin (PRANOTO *et al.*, 2005; CHA *et al.*, 2003). Essential oils (EOs) (cinnamon, oregano, lemongrass) stand out as an alternative to chemical preservatives and their use in foods meets the demands of consumers for natural products. BURT (2004) reported that hydrophobicity is an important characteristic of EOs, which makes them able to pass through cell membranes and enter mitochondria, disturbing the internal structures and rendering the membranes more permeable.

Yet the application of EOs in foods is limited due to their impact on organoleptic food properties, variability of their composition, and their variable activity in foods due to interactions with food components. Nevertheless, the use of EOs to control microbial growth in foods has been proposed for several products including fresh-cut fruits and vegetables.

RAYBAUDI-MASSILIA *et al.* (2008b) studied the effect of malic acid and essential oils of cinnamon, palmarosa and lemongrass as natural antimicrobial substances incorporated into an alginate-based edible coating on the shelf-life of fresh-cut melon. The coating containing malic acid was effective in improving the shelf-life of fresh-cut melon from both the microbiological and physicochemical points of view in comparison with non-coated fresh-cut melon samples. The incorporation of the essential oils or their active compounds into the coating prolonged the microbiological shelf-life by more than 21 days in some cases, probably due to an enhanced antimicrobial effect of malic acid and the essential oils. However, some physicochemical characteristics, such as firmness and color, and also some sensory quality attributes were adversely affected, causing a significant reduction of fresh-cut melon shelf-life. In contrast, when malic or lactic organic acids incorporated in soy protein coatings were applied to fresh-cut cantaloupe, they did not adversely affect the sensory properties of the fruit after cold storage (ESWARANANDAM *et al.*, 2006). AYALA-ZAVALA *et al.* (2013), developed an edible pectin film enriched with the essential oil from cinnamon leaves and proved that this application can increase the antioxidant status and reduce bacterial growth of fresh-cut peach. Chitosan coatings enriched with bioactive compounds (bee pollen, ethanolic extract of propolis, pomegranate dried extract, resveratrol)/essential oils (tea tree, rosemary, clove, oreganum, lemon aloe vera calendula) could be a good alternative for controlling not only the microorganisms present in broccoli, but also the survival of *E. coli* and *L. monocytogenes* inoculated in the product, without introducing deleterious effects on the sensory attributes of minimally processed broccoli (ALVAREZ *et al.*, 2013).

ROJAS-GRAU *et al.* (2006, 2007a) have studied the effects of oregano, cinnamon, and lemongrass oils and their active compounds (carvacrol, cinnamaldehyde and citral) incorporated into apple puree and alginate apple puree edible films against *Escherichia coli* O157:H7. In these works, oregano oil or its active compound, carvacrol, was most effective against *E. coli* O157:H7. In line with these preliminary studies, ROJAS-GRAU *et al.* (2007b) combined the efficacy of alginate and gellan edible coatings with the antimicrobial effect of EOs (lemongrass, oregano oil and vanillin) to prolong the shelf-life of fresh-cut apples. A 4 log reduction of the inoculated population of *Listeria innocua* in fresh-cut apple was observed when lemongrass or oregano oils were incorporated into an apple puree alginate edible coating. In addition, the coating reduced respiration rate and ethylene production of coated fresh-cut apples. In a later work (RAYBAUDI-MASSILIA *et al.*, 2008a), the addition of cinnamon, clove and lemongrass essential oils or their active compounds, cinnamaldehyde, eugenol and citral into an alginate-based coating increased their antimicrobial effect, reduced the population of *E. coli* 0157:H7 by more than 4 log CFU/g and extended the microbiological shelf-life of "Fuji" apples for at least 30 days. According to these studies, AZARAKHSH *et al.* (2014), observed that the lemongrass incorporated into an alginate-based coating for fresh-cut pineapple, reduces the microbial growth of the product during storage time. According to the Institute of Food Science and Technology (IFST), 10^6 CFU/g is considered the limit of acceptance for shelf-life of fruit-based products (BIERHALS *et al.*, 2011). In fact, the coated samples with 0.3% and 0.5% lemongrass reached 10^6 CFU/g after 12 and 16 days, respectively. On the contrary, the application of tapioca starch/decolorized hsian-tsao leaf gum coatings on minimally processed carrots with antimicrobial agents (cinnamon oil and grape seed extract) had no beneficial effect on controlling the mesophile aerobics and psychrophiles. As a result, the respiration rate of the product increased (LAI *et al.*, 2013). Instead, in the case of fresh-cut "Fuji" apples, cinnamon oil incorporated in tapioca starch/decolorized hsian-tsao leaf gum (dHG) based edible coatings, significantly reduced the growth of microorganisms, respiration rate, CO_2 and ethylene production (PAN *et al.*, 2013). MANTILLA *et al.* (2013) studied the effects of a multilayered edible coating with a microencapsulated antimicrobial complex (beta-cyclodextrin and trans-cinnamaldehyde) on the quality and shelf-life of fresh-cut pineapple. They reported that trans-cinnamaldehyde affects the pineapple flavour. However, the application of this antimicrobial coating extended the shelf-life of samples to 15 days at 4°C by inhibiting microbial growth. The same edible coating was applied on fresh-cut watermelon (SIPAHI *et al.*, 2013) and similar results were obtained: this type of alginate coatings extended the shelf life of fresh-cut watermelon from 7 (control) to 12-15 days. A microencapsulated beta-cyclodextrin and trans-cinnamaldehyde complex was also incorporated into a multilayered edible coating made of chitosan and pectin. This coating extended the shelf life of fresh-cut papaya up to 15 days at 4°C while uncoated fruits did not last this long (< 7days). Moreover, the coating reduced the losses of vitamin C and the total carotenoid content (BRASIL *et al.*, 2012).

Antibrowning agents

Fresh-cut fruit processing operations can induce undesirable changes in colour and appearance of these products during storage and marketing. The phenomena is usually caused by the enzyme polyphenol oxidase (PPO), which in the presence of oxygen, converts phenolic compounds into dark colored pigments (ZAWISTOWSKI *et al.*, 1991). Application of antioxidant treatments such as dipping after peeling and/or cutting is the most common way to control browning of fresh-cut fruits. Ascorbic acid is the most extensively used to avoid enzymatic browning of fruit due to the reduction of the *o*-quinones, generated by the action of the PPO enzymes, back to the phenolic substrates (MCEVILY *et al.*, 1992). For example, the antioxidants citric and ascorbic acid were incorporated into methylcellulose-based edible coatings in order to control oxygen permeability and reduce vitamin C losses in apricots during storage (AYRANCI and TUNC, 2004). The combination of chitosan coating and sodium chlorite dip treatment on pear slices adversely affected the quality of the fruit, accelerating the discoloration of cut surfaces and increasing the PPO activity. On the contrary, coating sodium chlorite-treated samples with carboxymethyl chitosan significantly prevented the browning reaction and inhibited PPO activity. (XIAO *et al.*, 2011). The effect of coatings in combination with anti-browning agents (1% chitosan; 2% ascorbic acid + 0.5% $CaCl_2$) on minimally processed apple slices has been studied during storage by HAIPING *et al.* (2011). Chitosan-coating treatments effectively retarded enzymatic browning on minimally processed apples during storage and effectively retarded tissue softening.

As an alternative to ascorbic acid, several thiol-containing compounds, such as cysteine, N-acetylcysteine, reduced glutathione and 4-hexylresorcinol have been investigated as inhibitors of enzymatic browning (GORNY *et al.*, 2002; SON *et al.*, 2001). These compounds react with quinones formed during the initial phase of enzymatic browning reactions to yield colorless additional products or to reduce o-quinones to o-diphenols (RICHARD *et al.*, 1992). 4-hexylresorcinol, in combination with sodium erythorbate, was effective in maintaining the color of pear slices "Anjou" (COLELLI and ELIA, 2009). Furthermore, carboxylic acids (citric acid and oxalic acid) have also been suggested as effective antioxidant agents in fresh-cut fruits (JIANG *et al.*, 2004; PIZZOCARO *et al.*, 1993; SON *et al.*, 2001). The incorporation of antibrowning agents into edible coatings applied on fresh-cut fruits has been studied by various authors. The application of alginate edible coating in conjunction with antibrowning agents (ascorbic and citric acid) to mango cubes increased vitamin C content compared to mango cubes treated only with alginate coating or control cubes, preserving the color of fresh-cut mangoes and increasing the antioxidant potential of cubes (ROBLES-SÁNCHEZ *et al.*, 2013). Moreover, PEREZ-GAGO *et al.*, (2006) reported a substantial reduction in browning of fresh-cut apples when using a whey protein concentrate-beeswax coating containing ascorbic acid, cysteine or 4-hexylresorcinol. They observed a significant improvement of the efficiency of antioxidant agents when incorporated into the coating formulation, being the most effective treatment with 0.5% cysteine. BRANCOLI and BARBOSA-CÁNOVAS (2000) decreased surface discoloration of apple slices with maltodextrin and methylcellulose coatings including ascorbic acid. BALDWIN *et al.* (1996) found that a carboxymethyl cellulose-based coating with addition of several antioxidants, including ascorbic acid, reduced browning and retarded water loss of cut apple more effectively than an aqueous solution of antioxidants. Furthermore, ROJAS-GRAÜ *et al.* (2008) observed that both alginate and gellan edible coatings containing N-acetylcysteine prevented apple wedges from browning during 21 days of storage. More recently, the application of konjac glucomann (polysaccharide derived from the tuber of konjac, *Amorphophallus konjac*) with pineapple fruit extract represents an effective alternative to prevent browning of fresh-cut Taaptimjaan rose apple fruit during storage. This coating enhanced total phenols and inhibited both PPO and peroxidase (POD) activities (SUPAPVANICH *et al.*, 2012). Or even, pullulan-based coating treatments in combination with antibrowning and antibacterial agents (1% pullulan; 0.8% glutathione + 1% chitooligosaccharides) effectively inhibited enzymatic browning, retarded tissue softening, inhibited microbial growth, decreased weight loss and respiration rate of the minimally processed apple slices (WU and CHEN, 2013).

Nutraceuticals

Nutraceuticals can also be incorporated into the formulation of edible coatings. Despite the growing interest in incorporating nutraceutical compounds into food products, few studies have suggested their integration into edible films or coatings. In this sense, the concentration of nutrients added to the films/coatings must be carefully studied since it is important to know the effects on their basic functionality, namely on their barrier and mechanical properties. Some studies have reported the effect of the addition of active compounds in the functionality of edible films. For instance, MEI and ZHAO (2003) evaluated the feasibility of milk protein-based edible films to carry high concentrations of calcium (5 or 10% w/v) and vitamin E (0.1% or 0.2% w/v). They concluded that protein-based edible films can carry active compounds, although the film functionality can be compromised. In contrast, PARK and ZHAO (2004) reported that the water barrier property of the chitosan-based films was improved by increasing the concentration of mineral (5and 20% w/v zinc lactate) or vitamin E in the film matrix. Nevertheless, the tensile strength of the films was affected by the incorporation of high concentrations of calcium or vitamin E, although other mechanical properties, such as film elongation, puncture strength, and puncture deformation, were not affected. Several researchers have endeavoured to incorporate minerals, vitamins and fatty acids into edible film and coating formulations to enhance the nutritional value of some fruits and vegetables, where these micronutrients are present in low quantities. TAPIA *et al.* (2008) reported that the addition of ascorbic acid (1% w/v) to the alginate and gellan based edible coatings helped to preserve the natural ascorbic acid content in fresh-cut papaya, thus helping to maintain its nutritional quality throughout storage. In the last few years, attention has been paid to the addition of probiotics to obtain functional edible films and coatings. TAPIA *et al.* (2007) developed the first edible films for probiotic coatings on fresh-cut apple and papaya, observing that both fruits were successfully coated with alginate or gellan film-forming solutions containing viable *bifidobacteria*. In fact, values higher than 10^6 cfu/g *Bifidobacterium lactis* Bb-12 were maintained for 10 days during refrigerated storage of both papaya and apple pieces, demonstrating the feasibility of these polysaccharide coatings to carry and support viable probiotics on fresh-cut fruits.

Alginate offers the possibility of formulating a broad range of functional and innovative food products, increasing the nutritional properties of foods. Recently, an edible alginate coating containing prebiotics such as oligofructose and inulin has been applied on fresh-cut apples wedges. Fructan analysis showed that all prebiotics remained stable over the 14 day storage period and sensory and visual assessment indicated acceptable quality of apple wedges coated with prebiotics (RÖßLE *et al.*, 2011). The addition of prebiotics could be especially appealing to consumers as they are essential to human nutrition in the context of dietary guidelines.

However, more studies are necessary to understand the interactions among active ingredients and coating materials when developing new edible film and coating, before they are applied to the surface of a real food system (ROJAS-GRAÜ *et al.,* 2009).

Further progress comes from nanotechnology, a science that could provide new techniques for extending the shelf-life of foods. Among the inorganic agents, silver nanoparticles have received great attention from the scientific world, due to the high biocidal effects towards many species of microorganisms (KIM *et al.*, 2007). In a study by COSTA *et al.* (2012), the effects of both active calcium-alginate coating loaded with silver-montmorillonite (Ag-MMT) nanoparticles and film barrier properties on the shelf-life of fresh-cut carrots were assessed. The results of this study suggest that the active coating is the best treatment and could be used to control both dehydration and microbial spoilage of minimally processed carrots. Moreover, the combination of coating with Ag-MMT controlled the microbial growth better than the sole coating treatment. The combined use of proper packaging and active coating allowed the carrots to be kept in a good state of preservation thus prolonging the shelf-life to about 70 days, with respect to the uncoated samples (about 4 days). However, the toxicological aspects of silver nanoparticles are well known (KIRUBA *et al.*, 2010; LU *et al.*, 2010); EU safety regulation limits the silver amount to 0.05 mg Ag/kg of food (FERNANDEZ *et al.*, 2009).

The application of edible coating either on fresh-cut apples or on fruits and vegetables are respectively summarized in Table 1 and in Table 2 (a and b).

Table 1 - Application of edible coating on fresh-cut apple.

Food product	Coating	Composition	Main results	References
"*Gala*" apple	Alginate	Alginate	Low weight loss; low enxymatic browning; greater firmness	OLIVAS *et al*. (2007)
Fresh-cut "*Fuji*" apple		Cinnamon, clove, lemongrass essential oil or their their active compound cinnamaldehyde, eugenol and citral	4 log reduction of the *E.coli* O157:H7population; shelf-life extension at least 30 days	RAYBAUDI-MASSILIA *et al*. (2008)
Fresh-cut apple wedges		Prebiotics, such as oligofructose and inulin	All prebiotics remained stable over the 14 days; good sensory characteristics	RÖßLE *et al*. (2011)
Fresh-cut "*Fuji*" apple	Alginate and gellan	Essential oils: lemongrass, oregano oil and vanillin	4 log reduction of the inoculated population of *Listeria innocua;* lower respiration rate and ethylene production	ROJAS-GRAÜ *et al*. (2007b)
Fresh-cut apple		Alginate or gellan film-forming solution containing viable *Bifidobacteria*	Higher values higher than 10^6 cfu/g of *Bifidobacterium lactis* Bb-12 were maintained for 10 days during refrigerate storage	TAPIA *et al*. (2007)
Fresh-cut apple		N-acetylcysteine	Enzymatic browning prevention during 21 days of storage	ROJAS-GRAÜ *et al*. (2008)
Apple slices	Methylcellulose coatings	Maltodextrin and ascorbic acids.	Decreased surface discoloration of apples slices	BRANCOLI *et al*. (2000)
Fresh-cut apple	Whey protein Concentrate beeswax	Ascorbic acid, cysteine or 4-hexyl-hexylresorcinol	Substantial reduction of browning	PEREZ-GAGO *et al*. (2006)
Apple "*Fuji*" slices		Ascorbic acid and citric acid	20% decrease of the respiration rate; shelf-life extension to 2 weeks.	LEE *et al.* (2003)
Apple slices	Carbohydrate/lipid bilayer film	Carbohydrate/lipid bilayer film	Water loss reduction	WONG *et al.* (1994)
Fresh-cut "*Fuji*" apple	Tapioca starch/decolorized hsian-tsao leaf gum	Cinnamon oil	Reduction of microbial growth, respiration rate, CO_2 and ethylene production	PAN *et al*. (2013)
Fresh-cut Taaptijaan rose apple	Konjac glucomannan	Pineapple fruit extract	Increase of total phenols; inhibi-tion of PPO and POD activities.	SUPAPVANICH *et al*. (2012)
Fresh-cut apple slices	Pullulan	Pullulan; glutathione and chitooligosaccharides	Delay of tissue softening, inhibition of microbial growth, decrease of weight loss and respiration rate.	WU and CHEN (2013)
Fresh-cut apple slices	Chitosan	Ascorbic acid and $CaCl_2$	Delay of enzymatic browning and tissue softening	HAIPING *et al*. (2011)

BIODEGRADABLE PACKAGING AND MINIMALLY PROCESSED FRUITS AND VEGETABLES

Fruits and vegetables are living organisms which continue to respire and transpire after harvesting, being characterized by a respiration rate; respiration and transpiration rates of fresh fruits and vegetables are often good indicators of their storage life; the higher the rate, the shorter the shelf-life (FLOROS, 1993). Moreover, the shelf-life of fresh-cut products is limited by microbiological deterioration and in order to reduce the effects of microbiological, chemical and physical events, it is possible to act on processing or, more usually, on packaging. The packaging operation should allow to establish inside the packaging an optimal atmosphere for the best preservation of the product. Generally, low and elevated atmospheres, together with low storage temperature, reduce the product respiration rate limiting, in this way, losses in fresh weight (WATADA *et al.*, 1996). The atmosphere that is established is the resultant of oxygen and carbon dioxide permeation through the walls of the packaging and of respiration

Table 2a - Application of edible coating on fresh-cut fruits and vegetables.

Food product	Coating	Composition	Main results	References
Sliced kiwifruit "Hayward"	Aloe vera	Aloe vera	Reduced O_2 consumption and CO_2 production; reduction of microbial spoilage	BENÍTEZ *et al*. (2013)
Sliced mango	Chitosan	Chitosan	Reduction of water loss	BICO *et al*. (2009)
Fresh-cut mango	Alginate and gellan	Ascorbic acid	Increase of Vitamin C	ROBLES-SÁNCHEZ *et al*. (2013)
Fresh-cut mango (pre-treated with citric acid dipping)	Cassava starch-edible coating	Cassava starch-edible coating	Reduction of weight loss and respiration rate; better maintenance of colour characteristics	CHIUMARELLI *et al*. (2010, 2011)
Sliced banana	Carrageenan	Carrageenan	Reduction of water loss	BICO *et al*. (2009)
	Soy protein	Soy protein, glycerol, malic acid, lactic acid	Good sensory characteristics	ESWARANANDAM *et al*. (2006)
Cantaloupe melon cube	Alginate	Malic acid and essential oils of cinnamon, pal- marosa and lemongrass	Microbiological shelf-life extension.	RAYBAUDI-MASSILIA *et al*. (2008)
Fresh-cut papaya	Alginate and gellan	Ascorbic acid	Preservation of the natural ascorbic acid content in papaya	MANTILLA *et al*. (2013);
	Chitosan and pectin	Microencapsulated anti-microbial complex (beta-cyclodextrin and trans-cinnamaldehyde)	Shelf-life extension to 15 days; reduction of vitamin C and total carotenoid content loss	SIPAHI *et al*. (2013)
Fresh-cut apple, papaya, pear, melon	Alginate	Alginate	Shelf-life extension to 15 days	FONTES *et al*. (2007); TAPIA *et al*. (2007); OMS-OLIU *et al*. (2008)
Fresh-cut pineapple, fresh-cut melon	Multilayered Sodium alginate coating	Microencapsulated antimicrobial complex (beta-cyclodextrin and trans-cinnamaldehyde)	Prevention of water loss	FONTES *et al*. (2007); TAPIA *et al*. (2007); OMS-OLIU *et al*. (2008)
Fresh-cut pineapple;	Cassava starch-edible coating	Calcium lactate/ potassium sorbate	Reduction of weight loss	BIERHALS *et al*. (2011)
Fresh-cut strawberries			Reduction of respiration rate	GARCIA *et al*. (2010)

Table 2b - Application of edible coating on fresh-cut fruits and vegetables.

Food product	Coating	Composition	Main results	References
Minimally processed pummel	Cassava or rice starch	Cassava or rice starch	Lower weight loss of 4.8–7.7% than the control	KERD-CHOECHUEN *et al*. (2011)
Fresh-cut peach	Pectin	Essential oil from cinnamon leaves	Reduction of bacterial growth; better antioxi- dant status	AYALA-ZAVALA *et al*. (2013)
Pear slices	Chitosan Carboxymethyl chitosan	Sodium chlorite	Increase of PPO activity Inhibition of PPO activity	XIAO *et al*. (2011)
Fresh-cut pineapple	Alginate	Lemongrass oil	Reduction of microbial growth	AZARAKHSH *et al*. (2014)
Fresh-cut broccoli, garlic	Chitosan	Chitosan	Reduction of meso- philic and psychrotrophic counts; inhibition of the yellowing and opening florets of fresh-cut broccoli	MOREIRA *et al*. (2011) GERALDINE *et al*. (2008)
Fresh-cut broccoli	Chitosan	Bioactive compounds (bee pollen, ethanolic extract of propolis, pomegranatedried extract,resveratrol)/essential oils (tea tree, rosemary, clove, oreganum, lemon aloe vera calendula)	Better control of microorganisms (*E. coli and L. monocytogenes);* good sensory attributes	ALVAREZ *et al*. (2013)
Fresh-cut carrots	Tapioca starch/decolorized hsian-tsao leaf gum	Cinnamon oil	No beneficial effect on controlling the meso- phyles aerobics and psychrophiles	LAI *et al*. (2013)
	Active calcium-alginate coating loaded with silver montmori-llonite (Ag MMTT) nanoparticles	High biocidal effects	Good control of dehy- dration and microbial spoilage; of shelf-life extension to about 70 days, with respect to the uncoated samples	COSTA *et al*. (2012)

by the cells, until reaching an equilibrium condition aimed to slow the senescence and avoid sensorial defects to the packaged product. Either high CO_2 or low O_2 concentrations could indirectly induce *off-flavours* by stimulating the growth of homo- and hetero-fermentative bacteria and yeast, which produce organic acids, ethanol and volatile esters (CARLIN *et al.*, 1989; KAKIOMENOU *et al.*, 1996). Therefore, a proper combination of product characteristics and film permeability, which is a fundamental characteristic of the packaging materials, results in the evolution of an appropriate atmosphere within packages (SMITH *et al.*, 1987). Moreover, the packaged food actually interacts with the packaging material, changing the initial mechanical and barrier properties of the packaging materials (PETERSEN *et al.*, 1999).

In alternative to the traditional polymeric materials, biodegradable films and coatings could be used. In fact, studies and experiments relating to possible applications of biodegradable materials, possibly combined with coating technique, to minimally processed fruits and vegetables are not lacking. Results obtained by using biodegradable films for samples of *Iceberg* lettuce are interesting: the film that is traditionally used to package fresh-cut salads is the bi-oriented polypropylene, which is associated with a level of senescence, linked to the metabolic activity of the vegetable, which is always higher than that achieved by salads packaged in biodegradable film. So, the potential application of biopolymers for the packaging of fresh-cut lettuce is justified (DEL NOBILE *et al.*, 2008). Also the rate of quality loss of minimally processed grapes in relationship with packaging film barrier properties has been assessed (DEL NOBILE *et al.*, 2009a). In earlier work, DEL NOBILE *et al.* (2008b) investigated the influence of postharvest treatments (ethanol, chlorinated water and hot water) on the quality loss kinetics of freshly processed grapes packaged in biodegradable films. The results suggested that ethanol is the best solution to preserve the microbial stability of the fresh produce without affecting its respiration rate to any great extent. Based on these results, clusters of table grapes (*Vitis vinifera* cv. Italia) were treated in ethanol solution prior to packaging in different bags made of two types of commercially available films (a multilayer film obtained by laminating nylon and a polyolefin layer (NP); an oriented polypropylene film (OPP)) and in three biodegradable polyester-based films (NVT-100, NVT-50, NVT-35). Results suggest that the respiratory activity of packed minimally processed produce is the main reason for its quality loss during storage. In fact, the best results in terms of grape quality were obtained using grapes with lower respiratory activity and high barrier films, such as NP and NVT-100. From a sensory point of view, no undesirable after-taste developed within the fruit, when the grapes were packaged in the thicker film (NP and NVT-100).

Also PLA has been tested for fresh-cut fruits and vegetables packaging; the coating of PLA silicon oxide (SiOx) improved the barrier oxygen and water vapor properties (PEELMAN *et al.*, 2013). In particular, the use of PLA containers with lids and pouches composed of VC999 Biopack PLA films coated with a barrier of pure SiOx to preserve quality of fresh-cut pears after 9 days of storage in comparison with conventional polyethylene PE material, has been investigated. The results showed that color and firmness color of fresh-cut pears is better maintained with biodegradable packaging materials (KRASNOVA *et al.*, 2013)

Biodegradable materials do not always fulfill the physiological requirements of the specific fruit and/or vegetable packaged in them: in fact, poor moisture barrier properties, linked to the hydrophilic character that marks most of the bio-based-materials, is sometimes responsible for higher percentages of weight loss in products, such as zucchini (LUCERA *et al.*, 2010), artichokes (DEL NOBILE *et al.*, 2009b) lampascioni (*Muscari comosum*) (CONTE *et al.*, 2009c) and melon (CONTE *et al.*, 2009b).

Often in several experiments, the technique of coating is used as a pretreatment to improve the performance of biodegradable materials and its effects on product quality. The coating treatment, containing sodium alginates, has been more effective than the *dipping* in delaying the metabolic activity associated to respiration rate in samples of lampascioni, subsequently packaged in NTV2, a film based biodegradable polyester (CONTE *et al.*, 2009c). Moreover, the browning process decreased, as well as, the microbial growth, since the availability of oxygen on the surface of the product was reduced. The same type of coating was also applied to fresh-cut artichokes (DEL NOBILE *et al.*, 2009 b): also in this case, the coating together with packaging in NTV2 film seems to represent the better strategy to preserve the quality of artichokes, also from a microbiological point of view. Interesting results also came from a study of fresh-cut cactus-pear: the shelf life of the minimally processed fruit, coated with an alginate and then packed with monolayer film (based on a blend of biodegradable polyesters), was prolonged to about 13 days, corresponding to an shelf-life increase of about 40%, compared to the control sample (untreated sample); on the contrary, produce immersion into either agar or fish protein strongly reduced the shelf life, most probably due to water migration from the surrounding hydro-gel to the fresh-cut produce (DEL NOBILE *et al.*, 2009 c).

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PLA is also been used in combination with silver; silver ions have been incorporated into polylactic film, in order to evaluate the silver-infused PLA films for inactivation of Salmonella and feline calicivirus in vitro and on fresh-cut vegetables (MARTÍNEZ-ABAD *et al.*, 2013). The results showed that in vitro the antibacterial and antiviral activity is more efficient than on food samples. Anyway, in lettuce samples incubated a 4°C at 6 days of storage, 4 log CFU of Salmonella was inactivated for film with 0.1% wt of silver ions and no viral infection has been found in the same conditions (MARTÍNEZ-ABAD *et al.*, 2013).

The results of the case studies on biodegradable packaging applied to fresh-cut fruits and vegetables and in some cases combined with edible coating are summarized in Table 3.

CONCLUSIONS

Foodstuffs are dynamic systems with a limited shelf-life and specific requirements in terms of packaging. In order to ensure the highest standards of product quality, the right combination of product characteristics and packaging film is the basis for the development of appropriate storage conditions.

This work focuses on the potential applications of biodegradable packaging and edible coating for minimally processed foods. The results highlight how the biodegradable films may have a more or less advantageous performance in relation to the physiological characteristics of

Table 3 - Application and combination of biopolymer with coating for fresh-cut fruits and vegetables packaging.

Food product	Biopackaging	Property of materials	Main results	Reference
Iceberg lettuce	Polyester-based biodegradable film	Good gas barrier properties	Shelf-life extension	DEL NOBILE *et al.* (2008)
Table grape (*Vitis vinifera*)	Polyester-based biodegradable film /nylon and polyolefin layer (ethanol pre-treatment before packaging)	High gas barrier	Good microbiological stability; good sensory characteristics	DEL NOBILE *et al.* (2009)
Zucchini (*Cucurbita pepo*)	Biodegradable co-extruded polyesters	High permeability to water vapor	High percentage of weight loss	LUCERA *et al.* (2010)
Artichoke	Biodegradable monolayer film based on a blend of biodegradable polyesters	Permeability to water vapor	High percentage of weight loss; good microbiological stability	DEL NOBILE *et al.*(2009)
	Coating with sodium alginate (pre-treatment before packaging)	Barrier to water vapour	Shelf-life extension (200%) low water loss	
Lampascioni (*Muscari comosum*)	Polyester-based biodegradable film	High permeability to water vapor	High percentage of weight loss	CONTE *et al.* (2009)
	Coating with sodium alginate (pre-treatment before packaging)	Barrier to water vapour and oxygen	Lower water loss; low microbial growth. reduced browning process	
Cactus pear	Monolayer film, based on a blend of biodegradable polyesters	High permeability to water vapour	High percentage of weight loss.	DEL NOBILE *et al.* (2009)
	Coating with alginates (pre-treatment before packaging)	Barrier to water vapour and other agents	Shelf-life extension to about 13 days	
Fresh-cut pears (*Pyrus communis*)	PLA films coated with a barrier of pure silicon oxide (SiOx)	Improved barrier properties	Better maintenance of color an firmness with respect to conventional PE packaging	KRASNOVA *et al.* (2013)
Melon	Blend of biodegradable polyester	High permeability to water vapor	High percentage of weight loss	CONTE *et al.* (2009)

complex matrices, such as fruit and vegetables, characterized by an active metabolism which significantly affects their conservation. Certainly, biopolymers fulfill the environmental requirements but they have some limitations in terms of performance, like thermal resistance, barrier and mechanical properties. Better results can be achieved by the combined use of biodegradable packagings with edible coatings.

The use of edible films and coatings represents an environmentally-friendly technology that offers substantial advantages for shelf-life prolongation of many food products, including fruits and vegetables. The development of new natural edible films and coatings with either inherent microbicidal activity or the addition of antifungal ingredients (food preservatives, essential oils, antagonistic microorganisms, etc.) to improve the quality of fresh-cut fruits and vegetables is a technological challenge for the industry and a very active field of research worldwide. Edible coatings can keep product characteristics, such as texture and hydration intact, and they can provide significant fruit senescence retardation. Moreover, they serve as a carrier for a wide range of food additives, including anti-browning or antimicrobial agents.

New challenges should focus on the development of tailor-made coatings, containing the most appropriate film forming constituents and active ingredients for fresh and minimally processed fruits and vegetables, according to specific industrial needs. New trends have shown that enrichment of biodegradable materials with silver-montmorillonite nanoparticles may be a promising technique.

Undoubtedly, biodegradation offers an attractive route to environmental waste management. However, the actual application of these packaging solutions to food is still limited, due to the high cost of raw materials and the small-scale production. In the future, when the quantities processed have increase to allow a change of scale, there will be a considerable reduction in the cost of biopolymers along with new and interesting applications in fresh-cut fruits and vegetables packaging.

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