Recent advances in modified atmosphere packaging and edible coatings to maintain quality of fresh-cut fruits and vegetables

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\textbf{Running title:} Advances in MAP and Edible Coatings for Fresh-Cut Products

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ABSTRACT

Processing of fruits and vegetables generates physiological stresses in the still living cut tissue, leading to quality deterioration and shorter shelf-life as compared with fresh intact produces. Several strategies can be implemented with the aim to reduce the rate of deterioration of fresh-cut commodities. Such strategies include low temperature maintenance from harvest to retail and the application of physical and chemical treatments such as modified atmosphere packaging (MAP) with low O$_2$ and high CO$_2$ levels and antioxidant dips. Other technologies such as edible coatings with natural additives, new generation of coatings using nanotechnological solutions such as nanoparticles, nanoencapsulation, and multilayered systems, and non-conventional atmospheres such as the use of pressurized inert/noble gases and high levels of O$_2$ have gained a lot of interest as a possibility to extend the shelf life of minimally processed fruits and vegetables. However, the high perishability of these products challenges in many cases their marketability by not achieving sufficient shelf life to survive the distribution system, requiring the combination of treatments to assure safety and quality. This review reports the recent advances in the use of MAP, edible coatings, and the combined effect of both technologies to extend the shelf life of fresh-cut fruits and vegetables.

Keywords: Minimally processed fruits and vegetables, edible coating, modified atmosphere packaging, hurdle technologies.
INTRODUCTION

Minimally processed or fresh-cut products are ready-to-eat or ready-to-use fresh fruits and vegetables that have been washed, chopped and packed in sealed polymeric films or trays. This trading form was developed in the 1980s to respond to the emerging consumer demand for convenient, high quality and preservative-free products that maintain fresh appearance, while being less severely processed than canned or frozen products. The demand for fresh-cut fruits and vegetables has continuously increased during the last few years, being the convenience factor the main reason for the growth, although now the healthy eating trend is helping to make this sector even stronger.

Contrary to other food processing techniques such as drying, freezing or canning, fresh-cut processing does not extend the shelf-life of the product. In fact, processing and packaging of fresh-cut fruits and vegetables generates physiological stresses in the still living cut tissues leading to quality deterioration and a shorter shelf-life as compared to intact fruits and vegetables (Gil et al., 2006; Rojas-Graü et al., 2009). The greatest hurdle to the commercial marketing of fresh-cut fruits and vegetables is their higher susceptibility to enzymatic browning, tissue softening, increasing of respiration, microbial growth, and environmental factors. Among them, temperature, humidity, atmospheric composition and ethylene concentration directly influence the deterioration process. Mechanical damage during harvesting, handling, storage and transportation before processing also reduces the shelf-life of the fresh-cut products.

There is no single technology that limits the overall quality deterioration. Several strategies can be implemented with the aim to reduce the rate of deterioration of fresh-cut commodities. These include the use of high quality raw produce harvested at optimum maturity, sanitation during handling and processing, reduction of mechanical damage during processing, and post-processing treatments such as low temperature and low oxygen atmosphere packaging to reduce
respiration rate and ethylene production. Other technologies such as edible coatings with natural
additives and non-conventional atmospheres have gained a lot of interest as a way to extend the
shelf life of minimally processed fruits and vegetables.

Successful applications of modified atmosphere packaging (MAP) with low O\textsubscript{2} and high CO\textsubscript{2}
for minimally processed fruits and vegetables have been extensively reported in the literature
(Rojas-Graü et al., 2009; Caleb et al., 2013; Zhang et al., 2015). The effect of low O\textsubscript{2} and high
CO\textsubscript{2} MAP to reduce quality deterioration of fresh-cut products during storage is related to a
reduction in respiration rate, ethylene biosynthesis, water loss, phenolic oxidation, and aerobic
microbial count. However, the beneficial quality effects of MAP on the packaged fresh-cut fruits
and vegetables depend upon a number of uncontrollable factors, such as the species, cultivar,
cultural practices, stage of development, postharvest handling, as well as controllable factors,
including packaging material gas permeability, respiration rate, and storage conditions (Kader
and Ben-Yehosua, 2000). Exposure of fresh-cut produce to too low O\textsubscript{2} and excessive CO\textsubscript{2} levels
may lead to anaerobic respiration and fermentation with the production of undesirable
metabolites and other physiological disorders. Therefore, the range of O\textsubscript{2} and CO\textsubscript{2} in the package
must be defined for each product and handling/processing characteristic (e.g. processed form,
package format, storage conditions, etc.).

Innovative MAP such as the use of pressurized inert/noble gases and high levels of O\textsubscript{2} (>70
kPa) have also been reported as effective in extending shelf life of minimally processed fruits
and vegetables (Kader and Ben-Yehoshua, 2000). The main benefits of superatmospheric O\textsubscript{2} and
noble gases atmospheres are related to the prevention of microbiological spoilage and anaerobic
fermentation, as observed in fresh-cut melon, cabbage, baby spinach, green peppers, broccoli,
and lettuce (Jamie and Saltveit, 2002; Allende et al., 2004; Oms-Oliu et al., 2008a; Lee et al.,
2011; Meng et al., 2012). Moreover, inert gases and high O\textsubscript{2} concentrations have been found to
be particularly effective at inhibiting enzymatic reactions and maintaining firmness of fresh-cut iceberg lettuce, mushrooms, potatoes, apples, green pepper, and melons (Amanatidou et al., 2000; Day, 2001; Jacxsens et al., 2001; Jamie and Saltveit, 2002; Limbo and Piergiovanni, 2006; Oms-Oliu et al., 2008a; Meng et al., 2012). Nevertheless, the effect of innovative MAP is dependent on similar factors as with conventional MAP (i.e. type of commodity, temperature, storage duration, etc.) (Kader and Ben-Yehoshua, 2000).

Another approach to extend the shelf life of fresh-cut fruits and vegetables is the use of edible coatings alone or combined with MAP. Edible coatings can provide a semipermeable barrier to gases and water vapor, which might translate in a reduction in respiration rate, enzymatic browning and water loss and their protective function may be also enhanced with the addition of ingredients such as antioxidants, antimicrobials, flavors, etc. (Pérez-Gago et al., 2005). Several reviews present the beneficial effect of edible coatings to maintain the quality properties of fresh-cut fruits and vegetables (Dea et al., 2012; Dhall, 2013). Considering the importance of these technologies in horticultural products, this paper provides a critical review about the most recent works in the literature regarding MAP and edible coating application, alone or in combination, to extend the shelf life of fresh-cut fruits and vegetables. The most recent studies on these technologies are summarized in Table 1.

**MODIFIED ATMOSPHERE PACKAGING**

MAP of fresh-cut products consists of enclosing the commodity in polymeric films in which the gas composition is modified from normal air to provide an atmosphere for increasing shelf life and maintaining the quality. Because of the respiration process, the fresh-cut product consumes O$_2$ and produces CO$_2$, therefore the O$_2$ and the CO$_2$ concentration within the package is reduced and increased, respectively. The steady state of equilibrium is reached when the
amount of O₂ consumed and CO₂ produced inside the package equals the O₂ and CO₂ amount permeating through the film. Therefore, the specific gas composition at equilibrium is determined by the product weight and physiology (e.g. respiration rate, maturity stage, etc), environmental conditions (e.g. temperature, relative humidity), and properties of the packaging material (e.g. film thickness, permeability, perforation density and surface area) (Caleb et al., 2013). The modified atmospheres can be achieved passively or actively. The passive MAP relies on the natural process of produce respiration and film permeability. While, active MAP is achieved by displacing the air within the package with a known mixture of gases to create an atmosphere that evolves during storage according to the produce respiration rate, the storage conditions and film permeability.

**Passive MAP for fresh-cut fruits and vegetables**

There is scarce information in literature about the effect of passive MAP on fresh-cut products compared to active MAP. Gil-Izquierdo et al. (2002) and Giménez et al. (2003) studied the effect of packaging films of different permeability (polyvinylchloride (PVC), low density polyethylene (LDPE) and polypropylene (PP)) on the quality (weight losses, color, texture and sensory acceptability) and microbial growth (mesophiles, psychrotrophs, anaerobic microorganisms, sporeformers, faecal coliforms, *Salmonella* and *Escherichia coli*) of minimally processed artichoke and observed that the highest permeability reached equilibrium rapidly and the highest atmosphere modification was detected with PP film. The atmosphere reached within the package affect the vitamin C and phenolic content (Gil-Izquierdo et al., 2002) and the microbial quality (Giménez et al., 2003) of minimally processed artichokes. Microbial counts were below the legal limit in those batches where the equilibrium atmosphere was anaerobic, whereas some batches with an acceptable sensory quality had microbial counts higher than those
allowed by the legislation. Similarly, Palma et al. (2013) reported lower microbial load in minimally processed cactus pear packed with low permeability PP films than in those packed with high permeability polyethylene (PE) films. Furthermore, fruits packed with microperforated films showed the highest microbial load. This was attributed in part to in-package gas composition and in part to a continuous contamination of microorganisms through micro-holes.

Escalona et al. (2007) studied the effect of passive MAP on quality attributes and shelf life of kohlrabi sticks during 14 days of storage at 0 °C. Two commercial films were tested (oriented polypropylene (OPP) and amide-polyethylene (amide-PE)) and compared to microperforated OPP film as control. On day 14 only sticks stored in MAP conditions scored above the limit of marketability; meanwhile, a poor appearance and slight tissue dehydration were observed in control sticks. The use of passive MAP helped maintaining firmness and induced a good fresh quality of sticks, especially when those were placed in amide-PE bags. Sticks packaged in this polymeric material reached an equilibrium atmosphere of 7 kPa O₂ and 9 kPa CO₂ after 6 days of storage and under these conditions the product presented an acceptable sensorial quality for 14 days.

Allende et al. (2004) studied the effect of PE film bags with two different O₂ permeabilities on plant metabolism, sensory quality and microbial growth of minimally processed baby spinach. Spinaches packaged in the higher barrier film (16.2 kPa CO₂) exhibited a more rapid accumulation of CO₂ than those in the permeable film (6.1 kPa CO₂) package at the end of 12 days of storage at 5 °C. Fresh-cut spinach packed with the barrier film exhibited a significant reduction in the growth of aerobic mesophilic bacteria compared to control conditions, but induced a strong off-odor and loss of tissue integrity due to the combination of extremely low O₂ and high CO₂ concentrations inside the packaging.
The application of antibrowning agents such as hexylresorcinol, potassium sorbate, and ascorbic acid in combination with passive MAP obtained with Cryovac LDX-5406 film reduced enzymatic browning and maintained the sensory quality of fresh-cut mangoes stored at 10 °C for 14 days (González-Aguilar et al., 2000). In any of the antioxidant treatments the O₂ and CO₂ concentrations at the end of the 14 days of storage were below 5 kPa or higher than 10 kPa, respectively. On the other hand, Beltrán et al. (2005) reported that the respiratory activity of potato strips packaged in LDPE in response to different sanitizers (traditional and non-traditional sanitizers) was similar for all treatments. After 5 days of storage at 4 °C, the steady state within packages was reached with O₂ and CO₂ levels of about 0.3–1.4 and 6.3–8.3 kPa, respectively.

The sanitizing treatments in vacuum packaging increased the lag phase of mesophilic bacteria up to 11 days, being the best packaging method to preserve the sensory quality of fresh-cut ‘Monalisa’ potatoes up to 14 days at 4 °C. In fresh-cut green bell pepper the application of 2% calcium propionate and subsequent packaging in Cryovac PD961 film maintained an equilibrium modified atmosphere of 13-14 kPa O₂ and 7 kPa CO₂, which helped to extend the microbial quality till 6 days storage at 8 °C (Ranjitha et al., 2015).

Packaging fresh-cut cantaloupe in passive MAP by sealing with Cryovac LDX-5406 film maintained its commercial shelf life for 9 days at 5 °C, whereas in similar perforated films (10 1.5-mm holes) shelf life was only 5 to 7 days, mainly due to tissue translucency and/or off-odor development (Bai et al., 2001). Similar results were found in fresh-cut honeydew melon harvested in two different seasons and packaged in a similar packaging system. Passive MAP extended the shelf life of honeydew melon by 1.3-3.7 days, depending on storage temperature, compared to those packaged in perforated films. Although quality attributes differed between cubes of fruit harvested in winter and summer, the shelf-life was similar for both winter and summer cubes stored under passive MAP (Bai et al., 2003). In a more recent work, Jayathunge et
al. (2014) determined the optimum maturity stage and micro-perforation level of PVC trays for fresh-cut papaya based on physico-chemical properties, and reported that packages with five and seven micro-perforations created anaerobic conditions and the accumulation of ethylene that negatively affected the overall quality of papaya cubes, whereas in packages with ten micro-perforations the concentrations of O\(_2\) and CO\(_2\) reached the equilibrium with 4 kPa and 6 kPa, respectively, and helped to maintain a storage shelf life of 19 days at 4 °C.

Low oxygen atmosphere-active MAP for fresh-cut fruits and vegetables (LOA)

MAs requirements for fresh-cut fruits and vegetables is low O\(_2\) (1–5 kPa) and/or elevated CO\(_2\) (5–10 kPa) levels to maintain quality and consequently extend shelf life of many products. In some cases, displacing the air within the package with a known mixture of gases close to the recommended atmospheres helps to extend the shelf life of the cut product by reducing the metabolism, delaying browning reactions, and inhibiting microbial growth as soon as the product is cut. Thus for example, fresh-cut honeydew and cantaloupe packaged in active MAP with 5 kPa O\(_2\) + 5 kPa CO\(_2\) and 4 kPa O\(_2\) + 10 kPa CO\(_2\), respectively, had better color retention, reduced respiration rate and microbial population, and longer shelf-life than those in passive MAP (Bai et al., 2001, 2003). In fresh-cut pears and melon, packaging under 2.5 kPa O\(_2\) + 7 kPa CO\(_2\) inhibited ethylene synthesis (Soliva-Fortuny et al., 2007; Oms-Oliu et al., 2008a, 2008b, 2009). However, O\(_2\) consumption and CO\(_2\) production rates of just-packaged fresh-cut pears were stimulated in a greater extend under 2.5 kPa O\(_2\) and 7 kPa CO\(_2\) atmospheres than under initial 21 kPa O\(_2\) (Oms-Oliu et al., 2008b). This phenomenon was attributed to a possible effect of the vacuum created in the package before flushing the gas mixture, promoting changes in the pear tissue structure, as well as a dramatic modification of the internal atmosphere. On the contrary,
Fresh-cut pears packaged in 21 kPa O\textsubscript{2} did not suffer such stress due to vacuum. This effect was only observed at early storage and decreased with storage time.

Effectiveness of LOA active MAP to control enzymatic browning, preserve visual appearance and extend the shelf life has also been reported in other fresh-cut products such as Galega kale (Fonseca et al., 2005) or pineapple (Marrero and Kader, 2006). However, in products rich in antioxidant compounds such as artichoke, pear, banana, persimmon, mango, papaya, nectarine, etc. the only use of LOA may be insufficient to prevent browning and provide sufficient shelf life to the cut product. Therefore, most of the works in the literature report the combine effect of antibrowning agents such as citric and ascorbic acid, cysteine, hexylresorcinol and MAP to control enzymatic browning and extend the shelf life of various fresh-cut produces as mango (González-Aguilar et al., 2000), pear (Gorny et al., 2002), banana (Vilas-Boas and Kader, 2006), and nectarine (Cefola et al., 2014). Thus in fresh-cut papaya, whereas LOA active MAP alone (5 kPa O\textsubscript{2} + 10 kPa CO\textsubscript{2}) or the antioxidant dip (CaCl\textsubscript{2} and citric acid) were not effective in preserving quality, the combination improved color, maintained firmness and reduced microbial count, which extended the shelf life of this product up to 25 days at 5 °C. Furthermore, the combination of antioxidants and active MAP showed a significantly lower decrease in O\textsubscript{2} concentration in the package and correspondingly lower increase in CO\textsubscript{2}, than untreated samples avoiding off-flavor development (Waghmare and Annapure, 2013).

Excessive low O\textsubscript{2} concentrations surrounding the fresh-cut product obtained by either passive or active MAP may accelerate the decay and the accumulation of fermentative metabolites leading to off-flavor and odors. Tudela et al. (2013) described severe off-odor development caused by ammonia accumulation in spinach after 10 days at 7 °C when exposed to low O\textsubscript{2} and high CO\textsubscript{2} (stabilizing near 1 kPa O\textsubscript{2} and 11 kPa CO\textsubscript{2}). Nevertheless, senescence of spinach occurred more rapidly in samples stored under higher O\textsubscript{2} (stabilizing near 10 kPa O\textsubscript{2} + 9 kPa CO\textsubscript{2}).
CO₂) concentrations. Soliva-Fortuny et al. (2007) observed that storage of fresh-cut pears under low O₂ and high CO₂ concentrations (2.5 kPa O₂/7 kPa CO₂) in low permeability PE bags was detrimental to flavor perception and even harmful to the fruit tissue after 3 weeks at 5 ºC. The increase in tissue softening and fermentative metabolites due to excessively low O₂ (<1 kPa) and high CO₂ (10-15 kPa), and ethanol accumulation in packages has also been observed in fresh-cut pears and melon (Oms-Oliu et al., 2008b, 2008c). However, Gunes et al. (2001) reported that elevated CO₂ (15 kPa) had an inhibitory effect on the accumulation of fermentation products in fresh-cut apples stored under 1 kPa O₂ atmospheres, resulting in about a 50% reduction in acetaldehyde, ethanol and ethyl acetate concentrations compared with 1 kPa O₂ in the absence of CO₂.

The effect of low O₂ and high CO₂ concentrations on the growth of Gram negative bacteria, moulds, and aerobic microorganisms, as *Pseudomonas* is well known. For example, packaging under active and passive LOA significantly inhibited the growth of spoilage microorganism in fresh-cut pears, melon, honey pomelo, nectarine, and mushroom slices, among others (Simón et al., 2005; Oms-Oliu et al., 2008b; Li et al., 2012a, Cefola et al., 2014) and reduced the development of aerobic psychrotrophic bacteria and *Pseudomonas* in leaf spinach (Tudela et al., 2013). The effect of MAP on microbial quality depends on the type and concentration of the microorganism, as well as the ripeness stage of the commodity and gas concentration at packaging. Oms-Oliu et al. (2009) observed that active MAP (2.5 kPa O₂ + 7 kPa CO₂) inhibited bacterial growth, yeast and mould proliferation in mature-green pears, but did not control microbial growth in partially ripe and ripe pears. On the other hand, mild abuse temperatures during storage of fresh-cut products under LOA can negatively affect their microbial quality. Thus, O’Beirne et al. (2015) observed the growth of *Listeria monocytogenes* on fresh-cut Iceberg
lettuce during storage at a constant temperature of 7 °C was enhanced at the lower oxygen MAP of 0.25 kPa O₂ + 12 kPa CO₂ by day 10, compared to a MAP of 2 kPa O₂ + 6 kPa CO₂.

Postharvest losses in nutritional quality, particularly vitamin C content, can be substantial and might be enhanced by physical damage, extended storage duration, high temperatures, low relative humidity, and chilling injury of chilling-sensitive commodities (Lee and Kader, 2000). Although the influences of processing and storage on the nutritional content of fresh-cut fruits seemed to depend on the commodity, storage under either passive or active MAP might reduce the rate of nutritional losses (Gil et al., 2006). In general, the range of O₂ availability is the main factor affecting antioxidant properties of fresh-cut products, whereas high CO₂ concentrations appear to have a significant effect on ascorbic acid, phenolic compounds and carotenoids. Fonseca et al. (2005) reported higher ascorbic acid degradation of shredded Galega kale in air than under 1–3 kPa O₂ atmospheres. Packaging of fresh-cut tomatoes under 2.5 kPa of O₂ and 5 kPa of CO₂ reduced the formation of carotenoids and maintained vitamin C during 21 days at 4 °C (Odriozola-Serrano et al., 2009). Aguayo et al. (2010) reported that passive MAP significantly reduced the loss of antioxidant activity and ascorbic acid concentrations of fresh-cut apples during storage at 4 °C, specially when apple slices were treated with calcium ascorbate. Others authors have reported that high concentrations of CO₂ (more than 5 kPa) had a negative effect on ascorbic acid maintenance of apple slices (Cocci et al., 2006) and fresh-cut pear (Oms-Oliu et al., 2007), especially when hypoxic conditions were reached in the packages. Similarly, total anthocyanin content in pomegranate arils was higher in clamshell packages than in MAP in low barrier bi-axial oriented polyester films (Banda et al., 2015). However, this was attributed to enhanced moisture loss in the clamshell package compared to MAP.

*High oxygen atmosphere for fresh-cut fruits and vegetables (HOA)*
The application of O$_2$ concentrations higher than 70 kPa has been found to be particularly effective at controlling aerobic and anaerobic microorganisms, preventing anaerobic fermentation and controlling enzymatic browning (Kader and Ben-Yehoshua, 2000). However, the effect greatly depends on the commodity, cultivar, physiological stage, and storage conditions.

The effect of high O$_2$ concentrations reducing microbial growth has been related to the accumulation of reactive oxygen species that damage vital cell components, affecting cellular antioxidant protection systems of cell metabolism (Kader and Ben-Yehoshua, 2000). O$_2$-enriched MAP (>85 kPa) reduced the growth of psychrotroptic microorganisms in fresh-cut Red Chard stored up to 8 days at 5 °C with 100 kPa O$_2$ (Tomás-Callejas et al., 2011) and fresh-cut pear and melon packaged in 70 kPa O$_2$ during storage at 4 °C (Oms-Oliu et al., 2008a, 2008b). Allende et al. (2004) also reported a reduced growth of mesophilic aerobes in fresh-cut baby spinach packaged in 80-100 kPa O$_2$ for 12 days at 5 °C. However, reports on the effect of high O$_2$ concentrations on the growth of aerobic microbiota on fresh-cut mixed salads were inconclusive (Allende et al., 2002). Lactic acid bacteria and Enterobacteriaceae bacteria appeared to be inhibited under high O$_2$ concentrations but, on the other hand, the growth of yeasts and *Aeromonas caviae* was stimulated under high O$_2$ levels, and psychrotrophic bacteria and *L. monocytogenes* were not affected. An inhibitory effect on some spoilage microorganisms such as *Rhodotorula mucilaginosa* yeast has also been observed in fresh-cut pears, ‘Piel de Sapo’ melons, mango cubes and honey pomelo when exposed to high O$_2$ concentrations (Poubol and Izumi, 2005; Oms-Oliu et al., 2008a; Li et al., 2012a). Whereas, *Candida parapsilosis* survived on inoculated cut pears stored under 70 kPa O$_2$ during 21 days at 4 °C (Oms-Oliu et al., 2008b). In strawberries, 80-100 kPa O$_2$ atmospheres inhibited the growth of *Botrytis cinerea* (Wszelaki
and Mitcham, 2000) and an initial atmosphere of 70 kPa O\textsubscript{2} retarded the growth of molds and yeasts on strawberries and raspberries stored 14 days at 5-7 ºC (Van der Steen et al., 2002).

The inhibitory effect on bacterial growth has been noticed to be greater when the high O\textsubscript{2} is combined with high CO\textsubscript{2} concentrations (10 to 20 kPa) rather than when the individual gas is used alone. Lee et al. (2011) suggested that high O\textsubscript{2} combined with CO\textsubscript{2} could give a bacteriostatic and bactericidal effect through suppression of aerobes by high CO\textsubscript{2} and anaerobes by high O\textsubscript{2}. Particularly, the antibacterial effect was evidently shown on \textit{E. coli} and \textit{S. aureus} among other inoculated strains (\textit{P. fluorescence}, \textit{S. Typhimurioum}, \textit{L. monocytogenes}) in fresh-cut cabbage. Amanatidou et al. (2000) also reported that packaging carrots slices under 50 kPa O\textsubscript{2} and 30 kPa CO\textsubscript{2} significantly inhibited the growth of Enterobacteriaceae bacteria, \textit{Pseudomonas} and lactic acid bacteria and shelf life was extended up to 15 days at 8 ºC. In fresh-cut bell peppers, MAP with 50 or 80 kPa O\textsubscript{2} and 15 kPa CO\textsubscript{2} controlled the growth of mesophilic, psychrotrophic bacteria and Enterobacteriaceae family up to 8-9 days at 5ºC and maintained the sensory quality attributes; however, high O\textsubscript{2} alone did not prevent microbial growth (Conesa et al., 2007). In fresh-cut honeydew melon cubes, MAPs consisting of 50 kPa O\textsubscript{2} + 50 kPa CO\textsubscript{2} and 70 kPa O\textsubscript{2} + 30 kPa CO\textsubscript{2} had little effect on color and firmness, however samples packed in 50 kPa O\textsubscript{2} + 50 kPa CO\textsubscript{2} had appreciably lower populations of yeasts and lactic acid bacteria, and lower quantities of volatile organic compounds after 5 days of storage at 7 ºC (Zhang et al., 2013).

Beside the effect on microbial growth control, the application of superatmospheric O\textsubscript{2} may stimulate, have no effect, or lower the respiration rate of fresh-cut produces, depending on the commodity, cultivar, physiological stage, storage conditions, etc. (Kader and Ben-Yehoshua, 2000). Poubol and Izumi (2005) studied the physiological behavior of two fresh-cut mango cultivars held in high O\textsubscript{2} atmospheres (60 kPa) for 42 h at 5 ºC. The authors observed that the 60
kPa O$_2$ atmosphere reduced the respiration rate of ‘Carabao’ mango cubes slightly during storage at 5 °C, whereas the same high O$_2$ concentrations did not affect the respiration rate of ‘Nam Dokmai’ mango cubes. Escalona et al. (2006) observed that the application of 70-80 kPa O$_2$ concentrations combined with 10-20 kPa CO$_2$ successfully reduced respiration rate and prevented anaerobic fermentation of fresh-cut butter lettuce. In fresh-cut melon, active MAP with initial low O$_2$ levels (2.5 kPa) reduced in-package ethylene concentration, whereas superatmospheric O$_2$ levels (70 kPa) avoided anaerobic metabolism by reducing CO$_2$ production rate and preventing ethanol production during 3 weeks of storage at 4 ºC (Oms-Oliu et al., 2008a, 2008c). Similarly, high oxygen partial pressures (55 to 100 kPa) had an inhibitory effect on the anaerobic volatiles production in potato slices stored 10 days at 5 ºC (Limbo and Piergiovanni, 2006) and helped to maintain the overall sensory quality of pomegranate arils during 18 days at 5 ºC (Ayhan and Esturk, 2009). However, other works have shown contradictory results regarding the effect of high O$_2$ levels on respiration rate and volatile production. Thus, ‘Mollar de Elche’ pomegranate arils packed under HOA (≈90 kPa) or ‘Wonderful’ pomegranate arils packed under high O$_2$-high CO$_2$ atmospheres (30 kPa O$_2$ + 10-40 kPa CO$_2$) presented higher respiration rate than those packed under passive MAP or air conditions (Maghoumi et al., 2013; Banda et al., 2015). In fresh-cut pear, superatmospheric O$_2$ did not prevent the production of acetaldehyde and ethanol during storage at 4 ºC due to a stress response related at the same time with the highly oxidative environment and the accumulation of CO$_2$ within the package (Oms-Oliu et al., 2008b).

The application of high O$_2$ atmospheres has also been suggested as an alternative to low O$_2$ and moderate CO$_2$ concentrations to inhibit enzymatic browning. It has been hypothesized that high O$_2$ levels may cause substrate inhibition of the enzyme polyphenol oxidase (PPO), or alternatively, that high levels of colorless quinones formed in the oxidation reaction may cause a
feedback inhibition of the PPO (Day, 2001). In sliced mushrooms and fresh-cut melon, high oxygen atmospheres (70-95 kPa O_2) were particularly effective for inhibiting enzymatic browning as compared with low-oxygen atmosphere MAP (Jacxsens et al., 2001; Oms-Oliu et al., 2008a). Allende et al. (2004) reported lower tissue damage to spinach leaves in high O_2 packages (80 and 100 kPa) stored at 5 °C for 12 days. However, although high O_2 atmospheres (50 to 90 kPa) reduced enzymatic browning of minimally processed Iceberg lettuce compared with low O_2 (3 kPa), it promoted russet spotting development (López-Gálvez et al., 2015). This was related to an increase in ethylene production in the high O_2 MAP which intensifies some of the effects of this plant hormone on lettuce heads, such as russet spotting. In some commodities, high O_2 concentrations alone cannot effectively prevent browning of fresh-cut produce and required the combination with other hurdle technologies. Limbo and Piergiovanni (2006) showed the positive effect of high-oxygen partial pressures combined with dipping in acid solutions to control enzymatic browning of fresh-cut potato for 10 days at 5 °C. Gómez di Marco et al. (2012) reported that the best combination to reduce artichoke heads browning was the application of 80 kPa O_2 and lemon juice as antioxidant. However, Poubol and Izumi (2005) reported that the application of superatmospheric O_2 concentrations (60 kPa) to fresh-cut mango showed a similar or higher degree of browning than the use of ambient air conditions at 5 °C. Similarly, Gorny et al. (2002) reported that high O_2 (40, 60, 80 kPa) did not effectively prevent surface browning of fresh-cut pears.

The use of high oxygen concentrations has been shown to reduce firmness loss in several fresh-cut products such as sliced carrot (Amanatidou et al., 2000), shredded iceberg lettuce (Day, 2001), and fresh-cut melon (Oms-Oliu et al., 2008a, 2008c). According to Amanatidou et al. (2000), the effect of high O_2 atmospheres on firmness may be related to an inhibition on the
proliferation of pectolytic *Pseudomonas*. However, pear slices kept in air, 40, 60 or 80 kPa O₂ (balance N₂) all softened at similar rates (Gorny et al., 2002).

Few works have been published on the effect of high O₂ concentrations on the nutritional content of fresh-cut fruits and vegetables. Day (2001) described that high O₂ atmospheres had a beneficial effect on ascorbic acid retention on prepared lettuce. However, vitamin C content of fresh-cut pears packaged in 70 kPa O₂ was rapidly lost in comparison with those packaged in low O₂ atmosphere and reached the lowest concentrations after 35 days at 5 °C (Oms-Oliu et al., 2007). Similarly, ascorbic acid content and antioxidant capacity underwent a significant depletion in ready-to-eat honey pomelo slices packaged under high O₂ (75 kPa) atmosphere in comparison with low O₂ active (3 kPa 5 O₂ + kPa CO₂) and passive MAP (Li et al., 2012a). Li et al. (2012b) also reported the highest decrease in vitamin C in fresh-cut pears stored in 80 kPa O₂ packaging with more than 50% loss in vitamin C content after 12 days of storage at 4 °C; whereas, phenolic and anthocyanin contents of the samples packed in 80 kPa O₂ were 2.5 and 12 times higher, respectively, than those in the passive package, and 3 and 2 times higher than those in low O₂ package after 12 days of storage at 4 °C. Higher production of phenolic compounds was also observed by Odriozola-Serrano et al. (2009) in tomato slices packed under high O₂ (60-80 kPa) and passive MAP and stored at 4 °C, whereas vitamin C was decreased in high O₂ atmospheres. According to these authors, the increase on phenolic compounds in fresh-cut products under both passive MAP and high O₂ concentrations active MAP could be directly associated with a physiological response to stress conditions. The fresh-cut tomatoes stored in 80 kPa of O₂ atmospheres also scored higher on flavonols, lycopene, β-carotene, chlorogenic acid, and total antioxidant capacity than those packed under lower O₂ concentrations (2.5 or 10 kPa). Furthermore, lower hydrophilic antioxidant capacity was obtained in tomato slices stored in 80 kPa of O₂, whereas the antioxidant capacity of the lipophilic fraction was enhanced with oxygen...
availability inside headspace packages. These results indicate that the effect of high O$_2$ on the nutritional content of fresh-cut products may vary depending on the commodity, O$_2$ concentration, storage time and temperature.

Noble gases and other non-conventional atmospheres for fresh-cut fruits and vegetables

The use of noble gases such as Helium (He), Argon (Ar), and Xenon (Xe) to replace N$_2$ as the balancing gas in MAP is considered one of the major advances to preserve and extend the shelf life of fresh and minimally processed fruits and vegetables. He, Ar and Xe have been successfully applied in MAP and controlled atmosphere storage to reduce microbial growth and maintain the quality of fresh products (Jamie and Saltveit, 2002; Meng et al., 2012; Wu et al., 2012a, 2012b). The beneficial effect of noble gases Ar and He have been related to their solubility and diffusivity characteristics (Day, 2001; Jamie and Saltveit, 2012). The similar atomic size to molecular O$_2$ and higher solubility in water than N$_2$ and O$_2$ make probably inner gases more effective at displacing O$_2$ from cellular sites and enzymatic O$_2$ receptors with the consequence that oxidative deterioration reactions are likely to be inhibited (Day et al., 2001). Furthermore, replacing the N$_2$ with He/Ar may modify the diffusion of O$_2$, CO$_2$, and C$_2$H$_4$ in fresh commodities. These changes allow fresh commodities that experience internal low O$_2$ deficiencies at lower O$_2$ storage to tolerate the low O$_2$ environment better than they could tolerate in the presence of N$_2$ atmospheres (Jamie and Saltveit, 2002). Similarly, several studies have explored the use of nitrous oxide (N$_2$O) and pure N$_2$, alone or in combination with Ar, to maintain fresh produce quality because of the ability to reduce ethylene emission, inhibit fungal growth, and slow down sensory quality deterioration of fresh-cut commodities (Cocci et al., 2006; Banda et al., 2015; Cortellino et al., 2015).
Rocculi et al. (2005) reported that the use of 90 kPa Ar on fresh-cut kiwifruit was significantly effective at maintaining firmness values and slowing down respiration, but not at controlling color browning. Better results were obtained by packaging of kiwifruits under 90 kPa N$_2$O, limiting firmness loss and maintaining color values during 12 days of storage at 4 ºC. Tomás-Callejas et al. (2011) investigated the antimicrobial and quality effect of 100 kPa O$_2$, He-, N$_2$-, or N$_2$O-enriched active MAP compared to a passive MAP on fresh-cut red chard baby leaves at 5 ºC during 8 days of storage. No differences in microbial growth were observed between He-, N$_2$-, and N$_2$O-enriched MAPs and the passive MAP. The active MAP helped to retain better the vitamin C content compared with the passive MAP; whereas, total phenolics content drastically increased during storage in samples under O$_2$-, He-, and N$_2$-enriched MAP. Among the treatments tested in active MAP, He preserved the total chlorophyll content throughout the shelf life. In fresh broccoli, however, atmospheres containing 90 kPa Ar and 2 kPa O$_2$ (balance N$_2$) did not delay the loss of chlorophyll (Jamie and Saltveit, 2002). In a recent work, Cortellino et al. (2015) highlighted that the Ar and N$_2$O mixture (65 kPa N$_2$O + 25 kPa Ar + 5 kPa O$_2$ + 5 kPa CO$_2$) was less effective at inhibiting ethylene production of ‘Golden Delicious’ apple slices than the conventional MAP (90 kPa N$_2$ + 5 kPa O$_2$ + 5 kPa CO$_2$), even though both atmospheres were characterized by the same percentage of O$_2$ (5 kPa), whereas the Ar and CO$_2$ mixture (80 kPa Ar + 20 kPa CO$_2$) completely inhibit ethylene production during 11 days of cold storage at 4 ºC. The latest atmosphere (Ar + CO$_2$) was also the most effective to maintain fruit firmness, although the beneficial effect was significantly reduced by dipping fruit in antibrowning agents (ascorbic and citric acids). However, any of the MAP tested could effectively prevent browning in absence of the antibrowning treatment and the atmosphere with 80 kPa Ar displayed a contradictory behavior as it controlled browning in antibrowning-dipped samples but enhanced it in undipped ones. On the contrary, Rocculi et al. (2004) reported
positive results at inhibiting enzymatic browning of apple slices packed in atmospheres containing Ar-N_2O (65 kPa N_2O + 25 kPa Ar + 5 kPa CO_2 + 5 kPa O_2) and N_2O (90 kPa N_2O + 5 kPa CO_2 + 5 kPa O_2) compared to air and conventional MAP (90 kPa N_2 + 5 kPa CO_2 + 5 kPa O_2), which was related to a higher solubility these gases compared to N_2.

Under appropriate temperature and pressure conditions inner gases can form ice-like crystals called clathrate hydrates, in which molecules are trapped within cage-like structure of water molecules, lowering water activity in fresh-cut produce, thereby reducing the leaching of organic material from fresh-cuts and movement of microbes into deeper tissues in comparison to other pretreatments (Caleb et al., 2013). Based on this behaviour, Meng et al. (2012) reported that the application of pressurized Ar (2, 4 and 6 MPa) on fresh-cut green pepper packed with 5 kPa O_2 and 8 kPa CO_2 were able to maintain the cell integrity of the produce by inhibiting the production of malondialdehyde, as well as the activities of catalase and peroxidase. The treatments were also reported to reduce the proliferation of spoilage microorganisms such as coliforms, yeast and moulds. Wu et al. (2012a) studied the effect of high pressure Ar (150 MPa) on preserving fresh-cut apples at 4 ºC. The pressurized Ar reduced the respiration rate and ethylene production of fresh-cut apples. However, it caused some negative effects on color and firmness, which were overwhelmed by combining the pressurized Ar and antioxidant treatments with calcium chloride, citric and ascorbic acid. This combination reduced color change and firmness loss and maintained the sensory quality of fresh-cut apples for 12 days at 4 ºC. Similarly, fresh-cut pineapple treated with pressurized Ar (1.8 MPa) effectively maintained the quality and delayed the microbial growth of the product, reaching 6 days of shelf life at 4 ºC (Wu et al., 2012b). The shelf life of fresh-cut pineapple was further extended to 20 days at 4 ºC by treating the samples with high pressure Ar or N_2 (10 MPa) (Wu et al., 2012c). These treatments effectively reduced respiration rate, ethylene production, browning and loss of total phenols and...
ascorbic acid, while did not cause a significant decline in fruit firmness. These authors completed
the study comparing the effect of high pressure (1.8 MPa absolute) versus normal atmosphere
pressure of a combination of Ar and Xe (Ar:Xe = 2:9 partial pressure) on wound healing and
microbial growth in fresh-cut apples and pineapples inoculated with *E. coli* and *Saccharomyces
cerevisiae* and stored at 4 °C (Wu et al., 2013). The results showed that samples under high
pressure Ar + Xe mixed treatment exhibited a positive wound healing response due probably to
the increase in H$_2$O$_2$ production and the accumulation of phenolics and lignin during storage.
The enhanced wound healing ability provided by the high pressure Ar + Xe mixed treatment was
also found to contribute at the inhibition of the growth of *E. coli* or *S. cerevisiae* in tested apple
and pineapple samples. In a similar way, the application of Ar or a mixture of compressed noble
gases (Ar and Krypton) helped to maintain a better quality on fresh-cut green peppers compared
to untreated peppers. The noble gases reduced the respiration rate and vitamin C loss of fresh-cut
peppers compared to the untreated samples, but did not inhibit the PPO activity. Overall, mixed
Argon-Krypton samples presented lower mass loss and cell membrane permeability than the Ar
treatment alone (Raymond et al., 2013).

**EDIBLE COATINGS FOR FRESH-CUT FRUITS AND VEGETABLES**

Traditionally, edible coatings have been used as a tool to reduce the deleterious effects of
processing on fruit and vegetable tissues. An edible coating is a thin layer of edible material
formed on the surface of a fruit and vegetable that provides a semipermeable barrier to gases,
water vapor, and volatile compounds between the product and the surrounding atmosphere.
Therefore, edible coatings can contribute to extend the shelf life of fresh-cut fruits and
vegetables by reducing respiration rate, enzymatic browning, and water loss.
Compounds most commonly used to form edible coatings include polysaccharides as chitosan, alginate, cellulose, carrageenan, pectin, starch; proteins as whey, casein, soy protein; and lipids as carnauba, beeswax and fatty acids (Dea et al., 2012). Several works have described the beneficial effect of polysaccharide and protein-based edible coatings on reducing the respiration rate of fresh-cut produces, which has been attributed to their good oxygen barrier. Hence, lower CO₂ production has also been observed in fresh-cut apples, melons, and pears coated with an alginate-based edible (Rojas-Graü et al., 2007; Oms-Oliu et al., 2008d; Raybaud-Massilia et al., 2008a, 2008b) and in apple slices coated with whey protein (Lee et al., 2003).

The hydrophilic nature of proteins and polysaccharides usually requires the addition of lipids to improve the moisture barrier of the edible coatings. Lipids such as sunflower oil added to alginate, gellan or pectin-based coatings and stearic acid incorporated to methyl cellulose-based edible coatings have been proven to significantly reduce weight loss of fresh-cut apple, papaya and pear (Tapia et al., 2007; Olivas et al., 2003). However, some works have also reported that edible coatings based on gellan and carrageenan with no lipid incorporated also reduced water loss of fresh-cut apples, papaya and banana (Lee et al., 2003; Tapia et al., 2007; Bico et al., 2009). On the other hand, studies to optimize the performance of whey protein isolate coatings on fresh-cut apples prior to the incorporation of additives such as antioxidants showed that lipid and solid content also affected the degree of browning of the samples (Pérez-Gago et al., 2003). As beeswax and solid content of the formulation increased the browning index of the samples decreased. However, high beeswax or solid content imparted a whitish appearance to the coated apples that negatively affected the visual quality.

The functional properties of edible coatings for fresh-cut fruits and vegetables are usually enhanced by the incorporation of active ingredients such as antioxidants, texture enhancers, and antimicrobials to reduce enzymatic browning, texture loss, and the risk of pathogen growth on
food surfaces. Thus, fresh-cut pears were preserved from surface browning by a methyl cellulose coating containing ascorbic acid (Olivas et al., 2003) or alginate and gellan coatings containing N-acetylcysteine and glutathione (Oms-Oliu et al., 2008d). Browning of fresh-cut apples has also been controlled or reduced by carrageenan and whey protein-based coatings containing ascorbic acid, citric acid, cysteine or oxalic acid (Lee et al., 2003; Pérez-Gago et al., 2006), alginate and gellan coatings containing N-acetylcysteine (Rojas-Graü et al., 2008; Raybaudi-Massilia et al., 2008a) and chitosan coatings containing ascorbic acid (Qi et al., 2011). In carrot slices, artichoke heads and fresh-cut mangoes, alginate coatings with ascorbic or citric acid were also effective to control browning (Amanatidou et al., 2000; Del Nobile et al., 2009; Robles-Sánchez et al., 2013) and banana slices maintained a better visual quality with a carrageenan coating containing ascorbic acid and cysteine (Bico et al., 2009).

Calcium and its salts have been used as firming agents of a great variety of fresh-cut fruits and vegetables by helping to maintain cell wall integrity. Furthermore, the addition of calcium as a gelling agent to alginate, gellan and pectin-based edible coatings have also shown to be effective at maintaining firmness in several fresh-cut products such as apple (Rojas-Graü et al., 2007, 2008; Freitas et al., 2013; Pan et al., 2013), pineapple (Azarakhsh et al., 2014) and melon (Raybaudi-Massilia et al., 2008b). A recent study also shows that the combined treatment of chitosan and calcium chloride was the most effective treatment for fresh-cut honeydew melon, leading to less weight loss and increase in firmness as compared to the application of the individual treatments. Nanostructural analysis indicated that firmness retention was closely related to an improvement in the sodium carbonate-soluble pectin integrity via interactions between the pectin and calcium ions or protonated chitosan groups (Chong et al., 2015).

The use of edible coatings with antimicrobial properties has been considered a potential tool to improve the safety of fresh-cut products. Among the different coatings, chitosan has been
widely tested in fresh-cut fruits and vegetables for their antimicrobial properties. González-Aguilar et al. (2009) reported that dipping fresh-cut papaya in a chitosan coating suppressed mesophilic plate count, and the growth of molds and yeast. Moreira et al. (2011) also reported a significant reduction in total mesophilic and psychrotrophic bacteria counts, the inhibition of total coliforms and a decrease of inoculated \textit{E. coli} O157:H7 counts of fresh-cut broccoli during cold storage. Furthermore, chitosan coatings have also been effective to avoid color change during storage of fresh-cut products such as litchi, mushrooms, and apples (Dong et al., 2004; Eissa et al., 2007; Qi et al., 2011), reduce weight loss and maintain ascorbic acid and total phenolic content in fresh-cut litchi and shredded carrots (Dong et al., 2004; Pushkala et al., 2012), and delay texture changes in fresh-cut mushrooms (Eissa et al., 2007).

Incorporating antimicrobial compounds into edible coatings has been another approach to enhance the safety and extend the shelf life of ready-to-eat products. Several antimicrobial compounds have been investigated as for incorporation into edible coatings, including organic acids (acetic, benzoic, lactic, propionic, sorbic), polypeptides (lysozyme, peroxidase, lactoferrin, nisin) and plant essential oil (cinnamon, oregano, lemongrass, etc.). Among them, essential oils are the most studied antimicrobial ingredients incorporated into edible coatings against pathogenic microorganisms in fresh-cut products. However, in many cases effective concentrations adversely affected the sensory properties of coated produce, making necessary an optimization to achieve microbial control, while preserving overall quality. Thus, alginate-based coatings with 0.1% eugenol or 0.15% citral plus 0.1% eugenol and pectin-based coatings with 0.15% citral or 0.2% eugenol best maintained the overall acceptability and reduced microbial growth of fresh-cut apples (Guerreiro et al., 2016). Combination of lemongrass at 0.3 and 0.5% with an alginate-based edible coating (sodium alginate and sunflower oil) significantly reduced yeast, molds and total plate counts in fresh-cut pineapple (Azarakhsh et al., 2014). In other study,
the addition of palmarosa oil (0.3%) to a similar alginate-based coating inhibited the native flora and reduced *S. enteritidis* population while maintained the fresh-cut melon quality parameters (Raybaud-Massilia et al., 2008b). Chitosan, alone or combined with essential oils or bioactive compounds (propolis, resveratrol and tea tree essential oil), also inhibited the growth of mesophilic and psychrotrophic bacteria, and controlled *E. coli* and *L. monocytogenes* survival, avoiding deleterious effects on the sensory attributes of fresh-cut broccoli (Álvarez et al., 2012).

On the other hand, organic acid salts, such as potassium sorbate or sodium benzoate, and peptides, such as nisin, which are widely used by the food industry as safe antimicrobial food additives, have been less studied as edible coating ingredients to control microbial growth in fresh-cut fruit. A recent work on fresh-cut persimmon reported the beneficial effect of apple pectin-based coatings amended with antioxidant (1% citric acid plus 1% CaCl$_2$) and antimicrobial agents (0.2 and 0.4% potassium sorbate, 0.4% sodium benzoate or 500 IU mL$^{-1}$ nisin) to control enzymatic browning and microbial growth (Sanchís et al., 2016a). These coatings effectively reduced the populations of artificially inoculated *E. coli* and *S. enteritidis*, nisin-coating being the most effective, while for *L. monocytogenes*, only the nisin coating effectively reduced the bacterial population. Similarly, the application of cellulose films containing 7500 IU mL$^{-1}$ nisin inhibited the growth of *Staphylococcus aureus* and *L. monocytogenes* in processed mangoes (Teixeira-Barbosa et al., 2013). Narsaiah et al. (2015) also reported that a 2% alginate coating incorporated with 20% bacteriocin could be used to store minimally processed papaya for 3 weeks by reducing microbial counts compared to uncoated samples without compromising the physico-chemical quality.

Combination of chitosan with other polysaccharides has also shown to improve its functional properties. For example, a chitosan-methyl cellulose film applied as food wrapper inhibited the growth of inoculated *E. coli* and *S. cerevisiae* on fresh-cut melon and pineapple as compared to
un-wrapped fruit, or fruit wrapped in a commercial stretch film (Sangsuwan et al., 2008). In a comparative study between chitosan, *Aloe vera* and sodium alginate edible coatings on preserving quality and extending shelf life of minimally processed kiwifruit, only *Aloe vera* and chitosan formulated with acetic acid were effective to reduce microbial growth trough 12 days at 4 ºC; however chitosan coated slices were not accepted by the sensory panelists (Benítez et al., 2015).

A new generation of edible coatings is under development, which aims to incorporate and/or control release of active compounds using nanotechnological solutions such as nanoparticles and nanoencapsulation (Dhall, 2013). The most commonly nanomaterials studied in edible films and coatings are metal and metal oxides such as silver (Ag), zinc oxide (ZnO), titanium dioxide (TiO$_2$) and magnesium oxide (MgO), which are known by their antimicrobial properties. These have been successfully incorporated to edible films such as chitosan, alginate, carrageenan and gellan to improve mechanical and barrier properties. However, few works can be found about the use of edible coatings containing nanoparticles for fresh-cut fruits and vegetables. Costa et al. (2012) studied the effect of an active alginate based-coating loaded with silver-montmorillonite (Ag-MMT) in shelf life and microbiological quality of fresh-cut carrots. Enterobacteriaceae bacteria and mesophilic bacteria in the active-coated sample were found below $10^4$ and $5 \times 10^7$ CFU/g, respectively, that were set as the threshold for these microbial groups. Reduced cell loads by one or two log cycles of psychrotrophic bacteria, *Pseudomonas* spp. and yeasts were also observed in fresh-cut coated carrots. This coating also resulted effective at controlling dehydration and extended the shelf life of the carrots packaged in OPP films to more than 45 days. In fresh-cut kiwifruit, the combined application of ultrasound treatment and nano-ZnO incorporated to a chitosan-based edible coating slowed down ethylene and carbon dioxide
production, reduced the water loss and softening, delayed the senescence and significantly
extend the storage life of the product (Meng et al., 2014).

On the other hand, micro- and nano-encapsulation consists in the incorporation of active
compounds into edible coatings with the aim to control their release under specific conditions
(e.g., changes of pH, temperature, irradiation, osmotic shock). This technology protects the
encapsulated active compounds from moisture, heat or other extreme conditions and enhances
their stability and viability (Dea et al., 2012). Among the different active compounds, essential
oils are the most widely encapsulated materials. Hence, Alikhani-Koupaeei (2015) successfully
encapsulated rosemary essential oil into liposome to form liposomal oil, which was later
incorporated into a mucilage edible coating to extend the shelf life of fresh-cut banana. This
coating reduced weight loss and maintained the overall quality of the product for up to 9 days
after processing without affecting sensory quality.

The potential of chitosan as edible coating for fruits and vegetables has also attracted the
interest for the study of colloidal particles at the nano level to enhance its effectiveness. Luo et
al. (2013) studied the effect of chitosan coating, alone or in combination with nano-chitosan (40-50 nm) on browning and lignification of fresh-cut Zizania latifolia stored at 1 ºC for 12 days.
The results showed that nano-chitosan coating was more effective than chitosan to retard
browning and lignification of fresh-cut Z. latifolia by inhibiting browning and lignification-related enzyme activity. Similarly, chitosan nanoparticles of 110nm had higher antimicrobial
activity against moulds and yeasts, and mesophilic and psychrotrophic bacteria than the
conventional chitosan coating, while not affecting other quality attributes of fresh-cut apples
(Pilon et al., 2015).

In some cases, the dipping of fresh-cut fruits and vegetables into an edible coating is limited
by the difficult adhesion to the hydrophilic surface of the cut product. The multilayer coating
technique has been used as a good alternative to overcome these problems. The preparation of multilayer structures consists of consecutive dipping of the cut product into two or more coating solutions containing oppositely charged polyelectrolytes. Coatings prepared with this technique have been applied in fresh-cut produces as papaya (Brasil et al., 2012), pear (Medeiros et al., 2012), pineapple (Mantilla, 2013), watermelon (Sipahi et al., 2013), and melon (Poverenov et al., 2014a, 2014b). By using this technique, microencapsulated \( \beta \)-cyclodextrin and trans-cinnamaldehyde complex have been successfully incorporated into a multilayered edible coating made of chitosan and pectin (Brasil et al., 2012). This multilayered edible coating was very effective at inhibiting aerobic and psychrotrophic bacteria, yeast and mold growth of fresh-cut papaya and helped to extend the shelf life of the product up to 15 days at 4 \( ^\circ \)C. This coating maintained firmness, color, vitamin C and \( \beta \)-carotene content and had no negative impact on flavor of coated papaya, being more accepted by the panelists than control samples. Similarly, the application of a multilayered edible coating composed of 2% trans-cinnamaldehyde, 2% chitosan and 1% pectin helped extend the shelf life of fresh-cut cantaloupe up to 9 days at 4 \( ^\circ \)C (Martínón et al., 2014).

Similar systems have been prepared with sodium alginate and microencapsulated \( \beta \)-cyclodextrin and trans-cinnamaldehyde for fresh-cut watermelon (Sipahi et al., 2013) and pineapple (Mantilla et al., 2013). The multiplayer edible coatings were prepared by layer by layer deposition of sodium alginate coating with pectin and calcium ion (calcium chloride or calcium lactate). The order was chosen based on the poly electrolyte interaction among opposite charges to obtain a stable and uniform coating and consisted of five steps (Calcium-antimicrobial coating-Calcium-Pectin-Calcium). The multilayered edible coating extended the shelf-life of fresh-cut pineapple and watermelon stored at 4 \( ^\circ \)C for 15 days. The coating effectively reduced
the growth of psychrotrophic bacteria, yeasts and molds, and also helped to maintain color, pH, 
total soluble solids, and firmness values without affecting odor and flavor attributes of the fruit. 
Medeiros et al. (2012) also optimized nanolayered coatings based on carrageenan and lysozyme. 
The coating was successfully applied to fresh-cut ‘Rocha’ pear and controlled weight loss and 
maintained high and low values of the total soluble solids and the titratable acidity, respectively, 
after 7 days of storage at 4 ºC.

Comparing a layer by layer alginate-chitosan with single-layer coatings on fresh-cut melon, 
the multilayer coating was found to possess the beneficial properties of both ingredients, 
combining good adhesion to melon matrix of the inner alginate layer with antimicrobial activity 
of the outer chitosan layer, thereby reducing the bacteria, yeast, and fungi counts by 1-2 log 
CFU. Furthermore, the by-layer coating slowed down tissue softening compared to single-layer 
coatings, so that after 14 days of storage only these samples maintained an appreciable firmness. 
An unexpected benefit of the by-layer coating was that it prevented an increase in headspace 
CO₂ and ethanol concentrations compared to monolayer coatings and even of the non-coated 
control, which are the signs of hypoxic stress and off-flavor development in coated samples 
when the gas barrier is too high. This phenomenon was presumably related to swelling behavior 
of the chitosan layer in the humid atmosphere of the fresh-cut melon package, enhancing gas-
exchange properties of the by-layer coating, but at the same time reducing water vapor resistance 
(Poverenov et al., 2014a). Similarly, layer by layer gelatine-chitosan coatings also demonstrated 
superior performance than mono-layer and blended coatings in maintaining fruit firmness of 
fresh-cut melon. However, while the by-layer formulation demonstrated the most effective 
inhibition of the total microbial growth especially after 5-7 days of storage, the blended 
formulation demonstrated high antifungal activity after 11 days of storage (Poverenov et al., 
2014b).
As regards the commercial coatings tested on fresh-cut fruits and vegetables, most of them are based on cellulose derivatives combined or not with sucrose fatty acid esters such as Semperfresh (AgriCoat Industries Ltd., Berkshire, UK) and Nature-Seal (Ecoscience Product System Division, Orlando, FL). These have been applied to fresh-cut mango (González-Aguilar et al., 2008), carrots disks and mushroom slices (Farber et al., 2003; Cliffe-Byrness and O’Beirne, 2007) among others. However, recent works have applied commercial formulations of Nature-Seal to fresh-cut fruits such as apples as natural antibrowning solutions based on blends of vitamins and mineral salts (Alegre et al., 2013; Altisent et al., 2014). Another commercial coating that has been applied to fresh-cut pears and apples is the chitosan derivative Nutrisave (Nova Chem, Halifax, NS, Canada), which resulted effective reducing respiration rate and weight loss, and delaying microbial decay (Baldwin et al., 1995).

**COMBINATION MAP AND EDIBLE COATING FOR FRESH-CUT FRUITS AND VEGETABLES**

The use of MAP or edible coatings in association with low temperature storage represent two of the main approaches to preserve the quality of minimally processed fruits and vegetables. However, the high perishability of these products challenges in many cases their marketability by not achieving sufficient shelf life to survive the distribution system. Therefore, some attempts have been focused to extend the shelf life of fresh-cut commodities by combining both edible coatings and MAP technologies.

Mastromatteo et al. (2011) studied the effect of a sodium alginate edible coating enriched with active compounds (hydro-alcoholic solution and grape seed extract) and two MAP conditions (passive and LOA with 10 kPa O₂ + 10 kPa CO₂) on the quality of minimally processed kiwifruits and observed that the alginate-based coating increased the shelf life of the...
samples up to 14 and 12 days when packed in LOA and passive MAP, respectively, compared to 8 days for the control samples. Similarly, the quality of minimally processed carrots was extended from 12 to 15 days when the product was treated with 0.1% citric acid and coated with alginate prior to storage at 8 °C under active MAP (50 kPa O₂ + 30 kPa CO₂) (Amanatidou et al., 2000).

Sothornvit and Rodsamran (2010) studied the effect of a mango-based film to wrap fresh-cut mango in combination with LOA packaging (10 kPa O₂). The MAP, with or without the mango film wrap, extended the shelf life of fresh-cut mango to 6 days when stored at 5 °C. Whereas, at room conditions the combination of the LOA and the edible mango wrap significantly reduced off-flavor and extended the shelf life from 2-3 days to 4 days.

Campaniello et al. (2008) studied the possible use of chitosan coating to improve the safety and quality on fresh-cut strawberries packaged in high (80 kPa) or low (5 kPa) oxygen MAP at different temperature (4, 8, 12, 15 °C) of storage. The combination of coating and MAP resulted in a sensible improvement on the microbial quality, particularly at the highest temperatures. Conventional MAP contributed to better control psychrotrophic bacteria; whereas high O₂ MAP had a beneficial effect on sensorial characteristics, color and mesophilic bacteria inhibition. On the contrary, Simões et al. (2009) reported that microbial populations of carrots sticks were not influenced by chitosan-yam starch or passive MAP during 12 days at 4 °C. However, the coating preserved the overall quality by reducing whiteness and the combined application of the chitosan coating and moderate MAP conditions (10 kPa O₂ +10 kPa CO₂) enhanced phenolic content in carrot sticks, which was attributed to chitosan acting as an exogenous elicitor. The observed accumulation was suppressed by low O₂ and high CO₂ levels (2 kPaO₂ + 15-25 kPaCO₂) reached by the less permeable film, probably related to low PAL activity or induction of enzymatic systems responsible of PAL inactivation. Similarly, a starch coating reinforced with natural
smectite montmorillonite nanoparticles and passive MAP (15 kPaO$_2$ + 20 kPaCO$_2$ steady state) led to the preservation of the total antioxidant activity, the volatile and organic acids of minimally processed carrots (Guimarães et al., 2016).

The application of gamma irradiation and high O$_2$ - high CO$_2$ (60 kPa O$_2$ + 30 kPa CO$_2$) MAP significantly reduced the growth of aerobic microorganism on minimally processed carrots. The combination of these treatments with a calcium caseinate and whey protein isolated-based edible coating did not affect the microbial growth of the samples; however, the coating was needed to protect carrots against dehydration and whitening (Lafortune et al., 2005). Caillet et al. (2006) also evaluated the effect of an antimicrobial edible coating based on calcium caseinate containing trans-cinnamaldehyde, combined with high oxygen (60 kPa O$_2$ + 30 kPa CO$_2$) or air and gamma irradiation at 0.25 or 0.5 kGy on peeled carrots inoculated with *L. innocua*. The use of HOA contributed to completely inhibit the growth of *L. innocua* and lowered the radiation dose required for that purpose. The antimicrobial edible coating was needed to reduce the *L. innocua* growth when minimally processed carrots were packed under air.

The combination of optimized soy protein isolate-based antioxidant edible coatings and MAP has been evaluated on fresh-cut artichoke, eggplant and persimmon during storage at 5 ºC (Ghidelli et al., 2010, 2014, 2015). MAP conditions included active conventional MAP (5 kPa O$_2$ + 15 kPa CO$_2$), passive MAP, and high O$_2$ MAP (>50 kPa, balanced with N$_2$) and they were compared to atmospheric conditions as control. Minimally processed eggplants and artichokes were susceptible to tissue damage when packaged under active or passive MAP with low O$_2$ and high CO$_2$ levels, whereas high O$_2$ MAP (>30-50 kPa) resulted detrimental for the storage of fresh-cut persimmons. The combination of the soy protein coating with the different MAP did not extend the shelf life of artichoke slices, but helped maintain the antioxidant capacity of the product as compared to control packaging conditions during the 4-day commercial period.
reached (Ghidelli et al., 2015). Similarly, the coating in atmospheric conditions provided the best and cheapest approach for extending the shelf life of fresh-cut eggplants up to 9 days of storage (Ghidelli et al., 2014). On the contrary, the combination of the soy protein isolate-based coating with the active MAP packaging (5 kPa O\textsubscript{2} + 15 kPa CO\textsubscript{2}) showed a synergic effect in controlling tissue browning of fresh-cut ‘Rojo Brillante’ persimmon and maintain the visual quality above the limit of marketability up to 8-10 days of storage at 5 °C (Ghidelli et al., 2010). Sanchís et al. (2016b) reported that the combination of a pectin-based coating formulated with antibrowning and antimicrobial agents (1% citric acid + 1% CaCl\textsubscript{2} + 500 IU mL\textsuperscript{-1} nisin) and active MAP (5 kPa O\textsubscript{2}, balance N\textsubscript{2}) improved the visual quality of ‘Rojo Brillante’ persimmon slices compared to single treatments, being evaluated as very good at the end of the 9-day storage period at 5 °C. The antimicrobial pectin coating also reduced the growth of total aerobic mesophilic bacteria during storage at 5 °C and effectively stunted the growth of *E. coli*, *S. enteritidis* and *L. monocytogenes* in artificially inoculated fresh-cut persimmon. The effect of the antimicrobial coating towards Gram-positive and Gram-negative bacteria was attributed to the combination of nisin and the low pH achieved by citric acid.

**FINAL REMARKS**

This review presents several studies about MAP and edible coatings with promising results to improve the safety and extend the shelf life of fresh-cut fruits and vegetables. The higher susceptibility of these products to enzymatic browning, tissue softening, microbial growth, and loss of nutrients makes in many cases necessary to continue looking for alternatives to reach sufficient shelf life for commercial distribution of the product. Depending on the MAP conditions, much research is still required to avoid or retard fermentative reactions, off-flavor and loss of nutritional compounds. Innovative MAP such as the use of pressurized inert/noble
gases and high levels of O$_2$ have resulted effective in extending shelf life of different fresh-cut fruits and vegetables, being the main benefits the prevention of microbiological spoilage and anaerobic fermentation. Nevertheless, the effect of innovative MAP is dependent on similar factors as with conventional MAP, i.e. type of commodity, temperature, storage duration, packaging material, etc. Some of the promising area for development to improve quality of fresh-cut commodities could be the use of active MAP able to deliver active compounds and new packaging material to better match the respiration of fresh-cut fruits and vegetables.

On the other hand, the application of edible coatings with active compounds and the use of nanotechnological solutions, such as nanoparticles, nanoencapsulation, and multilayered systems, to improve the quality of fresh-cut products require more research to understand the interactions among active compounds and coating materials to avoid sensory and physiological disorders in the product.

New combinations of MAP with edible coatings can be a feasible way for improving microbial stability and quality of fresh-cut fruits and vegetables, thus extending their shelf-life. Exploration of these technologies in highly perishable fruits and vegetables (i.e. high susceptibility to enzymatic browning, loss of integrity, microbial spoilage) that have received little or no attention is also required to increase the offer of fresh-cut fruits and vegetables, providing producers and consumer’s products with sufficient shelf life and the maximal safety and quality.

**ACKNOWLEDGEMENTS**

The authors thank the Spanish “Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria” (INIA) and the European Union FEDER program for funding research in this topic (projects RTA-2006-00114-00-00, RTA-2009-00135-00-00, and RTA-2012- -00061-00-
The doctorate program of Christian Ghidelli was supported by the Valencian Institute of Agricultural Research (IVIA).

References


Table 1. Modified atmosphere packaging (MAP) and/or edible coating application, alone or in combination for fresh-cut fruits and vegetable.

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Atmosphere conditions</th>
<th>Coating material</th>
<th>Additives</th>
<th>Benefits</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td>0-10 kPa O₂ + 0-30 kPa CO₂</td>
<td>—</td>
<td>AA, CA, CaCl₂</td>
<td>Reduce respiration rates Reduce ethylene production Control browning Preserve visual appearance</td>
<td>Gunes et al., 2001</td>
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<tr>
<td></td>
<td></td>
<td>Carragennan, WPC</td>
<td>CA, OA</td>
<td>Reduce CO₂ production Inhibit browning Reduce water loss</td>
<td>Lee et al., 2003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WPC, BW</td>
<td>AA, Cys, 4-HR</td>
<td>Inhibit browning</td>
<td>Pérez-Gago et al., 2006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alginate, gellan,</td>
<td>N-acetylcytsteine, glutathione,</td>
<td>Maintain texture Reduce water loss</td>
<td>Rojas-Graü et al., 2007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sunflower oil, fatty acids</td>
<td>CaCl₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alginate, gellan,</td>
<td>N-acetylcytsteine, AA, CA</td>
<td>Reduce weight loss</td>
<td>Tapia et al., 2007</td>
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<tr>
<td></td>
<td></td>
<td>sunflower oil</td>
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<td></td>
<td></td>
<td>Alginate</td>
<td>N-acetylcytsteine, CaCl₂</td>
<td>Inhibit browning Maintain texture</td>
<td>Rojas-Graü et al., 2008</td>
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<td></td>
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<tr>
<td>Passive MAP</td>
<td>—</td>
<td></td>
<td>CaAsc</td>
<td>Control browning Preserve visual appearance Maintain antioxidants and vit C content</td>
<td>Aguayo et al., 2010</td>
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<tr>
<td></td>
<td></td>
<td>Chitosan</td>
<td>AA</td>
<td>Inhibit browning</td>
<td>Qi et al., 2011</td>
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<tr>
<td>Pressurized Ar (150Mpa)</td>
<td>—</td>
<td></td>
<td>CaCl₂, AA, CA</td>
<td>Reduce respiration rate and ethylene production Reduced color change and</td>
<td>Wu et al., 2012a</td>
</tr>
<tr>
<td>Product</td>
<td>Treatment</td>
<td>Results</td>
<td>Authors</td>
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<tr>
<td>Artichoke</td>
<td>Passive MAP</td>
<td>— —</td>
<td>Reduce weight loss, Maintain vit C and phenolic compounds content</td>
<td>Gil-Izquierdo et al., 2002</td>
<td></td>
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<tr>
<td></td>
<td>—</td>
<td>Alginate CA, CaCl₂</td>
<td>Inhibit browning</td>
<td>Del Nobile et al., 2009</td>
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<tr>
<td></td>
<td>80 kPa O₂</td>
<td>—</td>
<td>Lemon juice</td>
<td>Inhibit browning</td>
<td>Gómez di Marco et al., 2012</td>
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<tr>
<td></td>
<td>—</td>
<td>SPI-BW Cys</td>
<td>Inhibit enzymatic browning</td>
<td>Ghidelli et al., 2015</td>
<td></td>
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<tr>
<td></td>
<td>80 kPa O₂</td>
<td>SPI-BW Cys</td>
<td>Maintain visual quality, Maintain antioxidant capacity</td>
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<tr>
<td></td>
<td>5 kPa O₂ + 15 kPa CO₂</td>
<td>SPI-BW Cys</td>
<td>Induce tissue browning</td>
<td></td>
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</tr>
<tr>
<td>Banana</td>
<td>2-4 kPa O₂ + 5-10 kPa CO₂</td>
<td>—</td>
<td>AA, Cys, CaCl₂</td>
<td>Control browning</td>
<td>Vilas-Boas and Kader, 2006</td>
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<tr>
<td></td>
<td>—</td>
<td>Carragennan AA, Cys, CaCl₂</td>
<td>Inhibit browning, Reduce water loss</td>
<td>Bico et al., 2009</td>
<td></td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>Mucilage Encapsulated rosmary oil</td>
<td>Reduce weight loss, Maintain the overall quality of the product for up to 9 days</td>
<td>Alikhani-Koupaei, 2015</td>
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<tr>
<td>Broccoli</td>
<td>—</td>
<td>Chitosan —</td>
<td>Reduce total mesophilic and psychrotrophic bacteria growth, Inhibition of total coliform growth, Decrease of E. coli growth</td>
<td>Moreira et al., 2011</td>
<td></td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>Chitosan Propolis, resveratrol, tea tree essential oil</td>
<td>Inhibit mesophilic and psychrotrophic bacteria growth, Control E. coli and L monocytogenes growth</td>
<td>Álvarez et al., 2012</td>
<td></td>
</tr>
<tr>
<td>Cabbage</td>
<td>70 kPa O₂ +</td>
<td>— —</td>
<td>Inhibit microbial growth</td>
<td>Lee et al., 2011</td>
<td></td>
</tr>
</tbody>
</table>

- Sodium alginate, pectin
- Eugenol, citral
- Maintain sensory quality for 12 days at 4 °C.
- Maintain the overall acceptability and reduce microbial growth at the optimum essential oil concentration
- Alginate CA, CaCl₂
- Reduce weight loss
- Maintain the overall acceptability and reduce microbial growth at the optimum essential oil concentration
- Lemon juice
- Inhibit browning
- SPI-BW Cys
- Inhibit enzymatic browning
- SPI-BW Cys
- Maintain visual quality, Maintain antioxidant capacity
- 5 kPa O₂ + 15 kPa CO₂
- SPI-BW Cys
- Induce tissue browning
- 2-4 kPa O₂ + 5-10 kPa CO₂
- — AA, Cys, CaCl₂
- — Carragennan AA, Cys, CaCl₂
- — Mucilage Encapsulated rosmary oil
- — Chitosan —
- — Chitosan Propolis, resveratrol, tea tree essential oil
- — Chitosan Propolis, resveratrol, tea tree essential oil
- — Chitosan Propolis, resveratrol, tea tree essential oil
- — Chitosan Propolis, resveratrol, tea tree essential oil
- — Chitosan Propolis, resveratrol, tea tree essential oil
- — Chitosan Propolis, resveratrol, tea tree essential oil
- 70 kPa O₂ +
<table>
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<th>Material</th>
<th>Conditions</th>
<th>Treatment</th>
<th>Benefits</th>
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<tr>
<td>Carrot</td>
<td>15 kPa CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Alginate</td>
<td>Inhibit E. coli and S. aureus growth</td>
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<td>Carrot</td>
<td>50 kPa O&lt;sub&gt;2&lt;/sub&gt; + 30 kPa CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Alginate, CA, CaCl&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Inhibit Enterobacteriaceae, <em>Pseudomonas</em>, lactic acid bacteria growth</td>
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<tr>
<td>Carrot</td>
<td>60 kPa O&lt;sub&gt;2&lt;/sub&gt; + 30 kPa CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>CC, WPI</td>
<td>Reduce microbial growth</td>
</tr>
<tr>
<td>Carrot</td>
<td>CC</td>
<td>Cynnamaldehyde</td>
<td>Inhibit <em>L. innocua</em> growth</td>
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<tr>
<td>Passive MAP</td>
<td>Chitosan, yam starch</td>
<td>—</td>
<td>Prevent surface whitening</td>
</tr>
<tr>
<td>Passive MAP</td>
<td>Chitosan</td>
<td>—</td>
<td>Reduce weight loss</td>
</tr>
<tr>
<td>Passive MAP</td>
<td>Alginate</td>
<td>Ag-montmorillonite</td>
<td>Control dehydration and extend the shelf life</td>
</tr>
<tr>
<td>Passive MAP</td>
<td>Cassava strach</td>
<td>Smectite montmorillonite nanoparticles</td>
<td>Preserve the total antioxidant activity, the volatile and organic acids</td>
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<tr>
<td>Eggplant</td>
<td>SPI-BW</td>
<td>Cys</td>
<td>Inhibit enzymatic browning</td>
</tr>
<tr>
<td>Eggplant</td>
<td>80 kPa O&lt;sub&gt;2&lt;/sub&gt;</td>
<td>SPI-BW</td>
<td>Maintain visual quality</td>
</tr>
<tr>
<td>Eggplant</td>
<td>5 kPa O&lt;sub&gt;2&lt;/sub&gt; + 15 kPa CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>SPI-BW</td>
<td>Induce tissue browning</td>
</tr>
<tr>
<td>Kale</td>
<td>1-2 kPa O&lt;sub&gt;2&lt;/sub&gt; + 15-20 kPa CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>—</td>
<td>Control browning</td>
</tr>
<tr>
<td>Kiwi</td>
<td>10 kPa O&lt;sub&gt;2&lt;/sub&gt; + 10 kPa CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Alginate</td>
<td>Control dehydration</td>
</tr>
<tr>
<td>Kiwi</td>
<td>Chitosan and Nano-ZiO</td>
<td>—</td>
<td>Slow down ethylene and carbon</td>
</tr>
<tr>
<td>Product</td>
<td>Method</td>
<td>Parameters</td>
<td>Treatments</td>
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<tr>
<td>Kohlrabi</td>
<td>Passive MAP</td>
<td>—</td>
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<td>80 kPa O₂</td>
<td>—</td>
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<tr>
<td></td>
<td>70-80 kPa O₂ +</td>
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<td></td>
<td>10-20 kPa CO₂</td>
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<td>50 to 90 kPa</td>
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<td>3 kPa</td>
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<td>Litchi</td>
<td>—</td>
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<td>—</td>
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<tr>
<td>Mango</td>
<td>Passive MAP</td>
<td>—</td>
<td>AA, 4-HR, PS</td>
</tr>
<tr>
<td></td>
<td>60 kPa O₂</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>10 kPa O₂ + 0 kPa CO₂</td>
<td>Mango film</td>
<td>—</td>
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<tr>
<td></td>
<td>—</td>
<td>Alginate, sunflower oil</td>
<td>AA, CA, CaCl₂</td>
</tr>
<tr>
<td>Melon</td>
<td>2.5 kPa O₂ + 7 kPa CO₂</td>
<td>—</td>
<td>AA, CaCl₂</td>
</tr>
<tr>
<td>Environment</td>
<td>Modification</td>
<td>Benefits</td>
<td>Authors</td>
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</tr>
<tr>
<td>2.5 kPa O₂ + 7 kPa CO₂</td>
<td>— CaCl₂</td>
<td>Inhibit ethylene synthesis, Decrease CO₂ emission</td>
<td>OmshOliu et al., 2008a</td>
</tr>
<tr>
<td>70 kPa O₂</td>
<td>— CaCl₂</td>
<td>Reduce psychrotrophic growth, Inhibit <em>Rhodotorula mucilaginosa</em> yeast growth, Reduce CO₂ production, Prevent anaerobic fermentation, Inhibit browning, Reduce firmness loss</td>
<td>OmshOliu et al., 2008a, 2008b, RaybaudihMassilia et al., 2008b</td>
</tr>
<tr>
<td>— Alginate</td>
<td>Cinnamon, palmarosa, lemongrass, eugenol, geraniol, citral, malic acid, calcium lactate</td>
<td>Inhibit microbial growth, Inhibition native flora growth, Reduce S. enteritidis growth</td>
<td>RaybaudihMassilia et al., 2008b</td>
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<tr>
<td>70 kPa O₂</td>
<td>— CaCl₂</td>
<td>Reduce CO₂ production, Prevent anaerobic fermentation, Reduce firmness loss</td>
<td>OmshOliu et al., 2008c</td>
</tr>
<tr>
<td>— Chitosan, MC</td>
<td>Vanillin</td>
<td>Control microbial growth</td>
<td>Sangsuwan et al., 2008</td>
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<tr>
<td>— LbL alginate-chitosan</td>
<td>—</td>
<td>Improve adhesion, Slow down tissue softening, Enhance gas exchange properties, Reduce bacteria, yeast, and fungi counts</td>
<td>Poverenov et al., 2014a, 2014b</td>
</tr>
<tr>
<td>— Chitosan</td>
<td>CaCl₂</td>
<td>Reduce weight loss and increase firmness, Maintain color, Inhibit mesophilic and psychrotrophic growth</td>
<td>Chong et al., 2015</td>
</tr>
<tr>
<td>Mixed salad</td>
<td>95 kPa O₂</td>
<td>— —</td>
<td>Inhibit lactic acid bacteria, Enterobacteriaceae bacteria growth</td>
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<td>Mushroom</td>
<td>95 kPa O₂</td>
<td>— —</td>
<td>Inhibit browning</td>
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<td></td>
<td>&lt; 0.1 kPa O₂ + 15 kPa CO₂</td>
<td>— —</td>
<td>Inhibition of microbial growth</td>
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<tr>
<td>— Chitosan</td>
<td>—</td>
<td>Inhibit PPO activity, Maintain texture</td>
<td>Eissa, 2007</td>
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<tr>
<td>Fruit</td>
<td>MAP Conditions</td>
<td>Antioxidant/ Additive</td>
<td>Benefits</td>
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<td>-------------------------------------------------------------------------------</td>
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<tr>
<td>Nectarine</td>
<td>10 kPa O(_2) + 10 kPa CO(_2)</td>
<td>2% AA + 1% calcium lactate</td>
<td>Control browning, Reduce microbial load</td>
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<td></td>
<td>Papaya —</td>
<td>Alginate, gellan, sunflower oil</td>
<td>Reduce water loss</td>
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<td></td>
<td>—</td>
<td>Chitosan</td>
<td>Inhibit microbial growth</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>LbL Chitosan-Pectin</td>
<td>Maintained firmness, color, vitamin C and (\beta)-carotene content Inhibit aerobic and psychrotrophic bacteria, yeast and mold growth Extend shelf life to 15 d at 4 ºC</td>
</tr>
<tr>
<td></td>
<td>5 kPa O(_2) + 10 kPa CO(_2)</td>
<td>CA, CaCl(_2)</td>
<td>Reduce microbial growth, Control browning, Maintain texture</td>
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<tr>
<td></td>
<td>Passive MAP —</td>
<td>—</td>
<td>Optimum O(_2) and CO(_2) concentrations of 4 kPa and 6 kPa, respectively, helped to maintain a storage shelf life of 19 days at 4 ºC</td>
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<tr>
<td></td>
<td>—</td>
<td>Alginate Bacteriocin</td>
<td>Reduce microbial counts without compromising physico-chemical quality</td>
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<tr>
<td>Pear</td>
<td>0.25-0.5 kPa O(_2) + 5-10-20 kPa CO(_2)</td>
<td>AA, Cys, calcium lactate</td>
<td>Control browning</td>
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<tr>
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<td>40, 50, 60 kPa O(_2) (balance N(_2))</td>
<td>—</td>
<td>Neither control browning, nor firmness loss</td>
</tr>
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<td>—</td>
<td>MC, stearic acid, AA, PS, CaCl(_2)</td>
<td>Inhibit browning, Reduce weigh loss</td>
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<tr>
<td></td>
<td>2.5 kPa O(_2) + 7 kPa CO(_2)</td>
<td>AA, CaCl(_2)</td>
<td>Inhibit ethylene synthesis, Decrease CO(_2) emission, Control browning, Preserve visual appearance</td>
</tr>
<tr>
<td></td>
<td>2.5 kPa O(_2) + 7 kPa CO(_2)</td>
<td>N-acetylcysteine, glutathione</td>
<td>Inhibit microbial growth, Inhibit ethylene synthesis</td>
</tr>
<tr>
<td>Pressure Conditions</td>
<td>Solutions</td>
<td>Benefits</td>
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<tr>
<td>70 kPa O₂</td>
<td>—</td>
<td>N-acetylcysteine, glutathione</td>
<td>Decrease CO₂ production, Control browning, Preserve visual appearance</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>Alginate, gellan, pectin</td>
<td>Reduce CO₂ production, Inhibit psychrotrophic growth</td>
</tr>
<tr>
<td>2.5 kPa O₂ + 7 kPa CO₂</td>
<td>—</td>
<td>N-acetylcysteine, glutathione, CaCl₂</td>
<td>Inhibit ethylene synthesis, Decrease CO₂ production, Control browning</td>
</tr>
<tr>
<td>80 kPa O₂</td>
<td>—</td>
<td>—</td>
<td>Increase production of phenolics compounds and anthocyanin</td>
</tr>
<tr>
<td>Pepper</td>
<td>50-80 kPa O₂ + 15 kPa CO₂</td>
<td>—</td>
<td>Control mesophilic and psychrotrophic bacteria, Enterobacteriaceae bacteria growth</td>
</tr>
<tr>
<td>Ar+Krypton (2 MPa)</td>
<td>Ar (2 MPa)</td>
<td>—</td>
<td>Reduce respiration rate and vitamin C loss</td>
</tr>
<tr>
<td>Persimmon</td>
<td>—</td>
<td>SPI CA, CaCl₂</td>
<td>Reduce browning</td>
</tr>
<tr>
<td>5 kPa O₂ + 15 kPa CO₂</td>
<td>SPI</td>
<td>CA, CaCl₂</td>
<td>Synergic effect to reduce browning</td>
</tr>
<tr>
<td>&gt;30 kPa O₂</td>
<td>SPI</td>
<td>CA, CaCl₂, PS, SB, nisin</td>
<td>Damage the tissue, Control browning and extended shelf life, Inhibit growth of mesophilic aerobic bacteria</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>Pectin CA, CaCl₂</td>
<td>Reduce the populations of artificially inoculated <em>E. coli</em> and <em>S. enteritidis</em>, while for <em>L. monocytogenes</em>, only the nisin coating was effective</td>
</tr>
<tr>
<td>Fruit/Condition</td>
<td>Oxygen</td>
<td>Carbon Dioxide</td>
<td>Chemicals/Ingredients</td>
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<tr>
<td>Pineapple</td>
<td>&gt; 8 kPa O&lt;sub&gt;2&lt;/sub&gt;</td>
<td>+ 10 kPa CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>— Chitosan, MC Vanillin</td>
</tr>
<tr>
<td></td>
<td>— Pressurized Ar (1.8 and 10 MPa)</td>
<td>—</td>
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<tr>
<td></td>
<td>— Pressurized N&lt;sub&gt;2&lt;/sub&gt; (10 MPa)</td>
<td>—</td>
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<td></td>
<td>— Pressurized Ar + Xe (Ar:Xe = 2:9)</td>
<td>—</td>
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<tr>
<td>Pomegranate arils</td>
<td>&gt;30 kPa O&lt;sub&gt;2&lt;/sub&gt;</td>
<td></td>
<td>LbL sodium alginate - pectin with Ca&lt;sup&gt;2+&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>100 kPa N&lt;sub&gt;2&lt;/sub&gt;</td>
<td></td>
<td>Alginate, sunflower oil</td>
</tr>
<tr>
<td>Pomelo</td>
<td>3 kPa O&lt;sub&gt;2&lt;/sub&gt; + 5 kPa CO&lt;sub&gt;2&lt;/sub&gt;</td>
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<tr>
<td></td>
<td>75 kPa O&lt;sub&gt;2&lt;/sub&gt;</td>
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<tr>
<td>Potato</td>
<td>55-100 kPa O&lt;sub&gt;2&lt;/sub&gt;</td>
<td></td>
<td>AA, CA</td>
</tr>
<tr>
<td>Red Chard</td>
<td>&gt; 85 kPa O&lt;sub&gt;2&lt;/sub&gt;</td>
<td></td>
<td></td>
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<tr>
<td>Vegetable</td>
<td>Passive MAP</td>
<td>O₂</td>
<td>CO₂</td>
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<tr>
<td>Spinach</td>
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<tr>
<td>Strawberry</td>
<td>80-100 kPa</td>
<td>—</td>
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<tr>
<td></td>
<td>70 kPa O₂</td>
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<tr>
<td></td>
<td>80 kPa O₂ + 20 kPa CO₂</td>
<td>Chitosan</td>
<td>—</td>
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<tr>
<td></td>
<td>5 kPa O₂ + 30 kPa CO₂</td>
<td>Chitosan</td>
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<tr>
<td>Tomato</td>
<td>2.5 kPa O₂ +5 kPa CO₂</td>
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<td></td>
<td>60 and 80 kPa O₂</td>
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</tbody>
</table>

**Notes:**
- AA = ascorbic acid, BW = beeswax, CaAsc = calcium ascorbate, CC = calcium caseinate, CaCl₂ = calcium chloride, CA = citric acid, Cys = cysteine, 4-HR = hexylresorcinol, LbL = layer by layer coating, MC = methylcellulose, OA = oxalic acid, PPO = polyphenol oxidase, PS = potassium sorbate, SB = sodium benzoate, SPI = soy protein isolate, WPC = whey protein concentrate, WPI = whey protein isolate.