

# **Innovative processes and technologies for modified atmosphere packaging of fresh and fresh-cut fruits and vegetables: A review**

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Modified atmosphere packaging (MAP) technology has been commercially viable since the 1970s. Currently, MAP is extensively used worldwide to preserve the quality and extend the shelf-life of whole fresh fruits and vegetables, but is also increasingly used to extend the shelf-life of minimally processed fresh fruit and vegetables. This review discusses new processes and technologies that have been developed to improve quality preservation and consumer acceptability of minimally processed produce where high respiration rates and challenging degradation processes operate. Adoption of packaging technology improvements will be critical in meeting expectations of consumers for minimally processed products to consistently have fresh-like quality and to enable producers and retailers to maintain quality for longer distribution and display periods. Innovative approaches to achieve further extension of shelf-life include active MAP with produce-specific differentially permeable films, films that incorporate antimicrobial properties, edible coatings that confer barrier properties, and the use of non-traditional gases to modify respiration. Intelligent packaging innovations are also appearing, using packaging integrated sensor technologies to indicate maturity, ripeness, respiration rate and spoilage of fresh produce. Additionally there are new

opportunities for incorporating logistics tracking technologies and consumer communication into the design of packaging. Preservation technologies and associated packaging developments that can be combined with modified atmosphere are constantly evolving technology platforms. Adoption of optimal combinations of technology improvements will be critical in responding to commercial trends towards more minimally processed fresh-cut and ready-to-eat fruit and vegetable products.

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## **1. Introduction**

Food packaging is the final operation of fresh produce processing that allows the products to be protected and safely distributed to consumers. Together with cold chain management, packaging allows the quality of fresh products to be preserved with extension of the shelf-life (Nicola and Fontana, 2014). There are increasing demands for extension of shelf-life to better meet longer and more global distribution chains, as well as rising consumer expectations for high and lasting quality in purchased fresh produce. Technologies for modified atmosphere packaged fresh whole produce and fresh-cut products are therefore continually evolving to meet these escalating needs for improved performance in shelf-life and quality retention.

Food packaging is of particular importance to fresh horticultural produce as quality can only be maintained after harvest and not improved. When optimized, food packaging increases the convenience, safety and quality of food for consumers, while reducing the need for additives, food waste and the incidence of food poisoning (Robertson, 2012). This can produce significant cost savings and competitive advantages for food retailers and manufacturers (Coles et al., 2003). Modified atmosphere packaging (MAP) is an increasingly important type of packaging, particularly for fresh fruits and vegetables (Sandhya, 2010) as it can lower respiration rate, delay ripening and discoloration, prevent the build-up of off odors and flavors and inhibit growth of pathogens and spoilage organisms (Zhang et al., 2015). This ultimately enables extended shelf-life attributes which can facilitate the development of wider food distribution networks along extended supply chains (Sonneveld 2000).

A further driver for improvements has been the increased consumer preference for more diverse and convenient forms of nutritious, fresh, healthy and easy to consume produce. Globally, the demand for fresh produce is increasing at a rate of 6% per annum (Dodd and Bouwer, 2014). Minimally processed products have a rapidly growing market particularly in

the US and the UK (Abadias et al., 2008; Kou et al., 2015). They are designed to maximize convenience for consumers, while maintaining freshness and nutritional quality (Oliveira et al., 2015). Minimally processed products are usually packed directly after harvest and processing and, ideally, are only handled once before reaching consumers (Sant'Ana et al., 2012). However, in contrast to many packaged prepared meals, minimally processed salad vegetables and fruits are not heat treated prior to consumption. They can therefore be especially prone to the presence of human pathogens or the growth of spoilage organisms that could limit shelf-life (Oliveira et al., 2015). Further, minimal processing can lead to increased respiration rates and therefore higher rates of deterioration (Santos et al., 2014), biochemical changes and microbial spoilage (Sant'Ana et al., 2011; Martínez-Sánchez et al., 2012). New packaging solutions are being sought to address the many mechanisms that degrade quality and safety.

In this review, we summarize recent MAP and associated packaging advances that have been developed to improve product quality and integrity, and provide greater benefits to consumers in fresh fruits and vegetables. In Section 2, we describe the key factors influencing the effectiveness of MAP of fresh fruits and vegetables and the areas that can be targeted for improvements. In Section 3, we profile the latest innovations in MAP technology, followed in Section 4 by a discussion on innovative packaging technologies that are complementary to MAP. In Section 5, we highlight the knowledge gaps that will need to be addressed to optimize the use of modern packaging technologies and technology combinations in the fresh fruits and vegetables industry.

## **2. Modified Atmosphere Packaging of Fresh Fruits and Vegetables**

Modifying gas composition for individual containers is referred to as MAP, and for bulk storage as MA. These are both designed to lower the respiration rate of the produce and influence the growth of microbial flora to extend the shelf-life of foods and contribute to improved food safety (Kader *et al.* 1989). This review focuses on MAP where both the packaging and gas atmospheres can be manipulated to help preserve the qualities of the produce.

Recent applications of MAP have been effective for both climacteric fruits such as avocado (Sellamuthu *et al.*, 2013), breadfruit (Roopa *et al.*, 2015) and figs (Villalobos *et al.*, 2014), and non-climacteric fruits such as pineapples (Finnegan *et al.*, 2013), cherries (Colgecen and Aday, 2015), and oranges (Barrios *et al.*, 2014). In general, for climacteric fruits, slowing respiration and ripening are the crucial functions of MAP, particularly for highly perishable fruits such as guava (Antala *et al.*, 2015) and mango (Ramayya *et al.*, 2012). Conversely, for both minimally processed non-climacteric fruits and vegetables, the role of MAP in preventing oxidative browning and the growth of microbial pathogens is of greater importance than slowing respiration and ripening processes (Horev *et al.*, 2012).

The shelf-life effects of MAP on a range of factors including organoleptic qualities (Sivakumar and Korsten, 2006; Díaz-Mula *et al.*, 2011; Fagundes *et al.*, 2015), bacteria growth (Posada-Izquierdo *et al.*, 2014), fungal (usually yeast) growth (Bastiaanse *et al.*, 2010; Caponigro *et al.*, 2010), coloring – particularly for anti-browning (Gomes *et al.*, 2012), fruit decay (Selcuk and Erkan, 2015) and prevention of chilling injuries (Cheng *et al.*, 2015), have been studied for a very wide range of minimally processed horticultural products. Finnegan *et al.* (2013) examined the effects of intrinsic factors (origin, physiological age and seasonality) and extrinsic factors (cut-size, blade-sharpness and dipping treatments) on respiration rate of

fresh-cut pineapple chunks and concluded that, in general, physiological age and origin were found to be more important than season in determining the effects of MAP on quality attributes and shelf-life.

## **2.1 Factors influencing effectiveness and design of MAP**

MA can be generated in the container passively by respiration of the fresh produce, as it consumes O<sub>2</sub> and produces CO<sub>2</sub>. Minimum O<sub>2</sub> and maximum CO<sub>2</sub> concentrations can be controlled by the balance of the gas permeability of the packaging film. However, these levels can be established more rapidly by actively gas flushing with the desired gas. In bulk MA storage, gas composition is continuously maintained through control of the storage atmosphere by adjustment to set points using a gas supply.

Low O<sub>2</sub> levels (1-5%) are frequently the primary means of shelf-life management of fresh produce in MAP. In early applications of MAP, the principal objective of reduced O<sub>2</sub> was to reduce the respiration rate of fresh fruits and vegetables to increase potential shelf-life.

However, low O<sub>2</sub> also inhibits the growth of aerobic microorganisms (Kader et al., 1989).

Recent studies have shown that low O<sub>2</sub> conditions can also prevent the development of desirable aromas in fresh melons (Amaro et al., 2012), or lead to the development of off-odors in baby spinach (Tudela et al., 2013) suggesting that new technologies based on low O<sub>2</sub> levels should take into account the characteristics of the produce to prevent the development of anaerobic respiration conditions.

Maintaining adequate CO<sub>2</sub> levels (3-20%) in addition to low O<sub>2</sub> levels is the most important factor in inhibiting aerobic microbes (Li et al., 2015; Wang et al., 2015). However, maximum levels of CO<sub>2</sub> tolerance can vary greatly depending on produce (Sandhya, 2010). These range

from 2% for apples and pears to 15% for berries and spinach (Kader et al., 1989) with high levels leading to physiological breakdown of tissue.

Maintaining high levels of relative humidity (85-95%) and reduced water loss (Kader and Watkins, 2000; Mangaraj et al., 2015) are a common outcome of MAP which can prove beneficial for many fresh fruits and vegetables. However, high relative humidity within MAP can also lead to increased pathogen growth, as seen with stem fungal growth on cherry tomatoes (Mistriotis et al., 2016), and should be managed to suit the commodity.

Minimizing ethylene exposure is also known to help extend shelf-life. Ethylene is a plant hormone that regulates the growth and senescence of plant material. It is produced endogenously by many fruits and vegetables and can spike as a result of fresh cut wounding responses, but is also used exogenously to accelerate ripening. Recent work on ethylene and non-climacteric produce, as reviewed by Wills (2015), has determined both its importance in controlling senescence of fruits and vegetables previously considered unaffected by ethylene, and shown that adequate control of ethylene can reduce the need for expensive and energy intensive cold chain distribution systems. Minimizing ethylene exposure is therefore also a target for fresh-cut technologies as it is vital in minimizing respiration and extending shelf-life of fresh produce (Wills, 2015). As ethylene levels can also play a major role in coloration, such as in tomato (Lee et al., 2012), technologies that inhibit or sense ethylene levels could be useful for managing color development of a range of fruits and vegetables, especially climacteric fruits such as guava (Kuswandi et al., 2013).

Factors that influence gaseous composition, such as packaging permeability, are important variables in MAP applications. Packaging permeability is a function of polymer type and thickness, and for some polymers, it is heavily influenced by temperature and gas pressure gradients (Petracek et al., 2002). Alternatively, gaseous composition can be modified by

micro-perforations in the film, which are typically 30-350  $\mu\text{m}$  and often of elliptical shape (González-Buesa et al., 2013). The native extent and form of perforation such as size, shape, and method of hole production, have been shown to be crucial in determining the effectiveness of MAP (Elwan et al., 2015). A further refinement of micro-perforation is the development of microporous films, where inert compounds are inserted into a film to create microscopic pores typically 0.1-1.5  $\mu\text{m}$  wide (Scafati et al., 2013). Such films allow for very accurate control of gas permeability, and will become increasingly important to preserving fresh produce in MAP.

## **2.2 Areas for improvements for MAP**

MAP applications have not always proven effective in increasing the shelf-life and safety of fresh produce (Li et al., 2015). For whole produce, the visual quality but not the organoleptic qualities of winter harvested iceberg lettuce was enhanced by MAP (Martínez and Artés, 1999). In broccoli, low  $\text{O}_2$  regimes ( $< 0.25$  kPa) applied to prevent yellowing also induced highly undesirable flavors and odors (Cameron, 2003). Studies on cherries have found that the effectiveness of MAP may be cultivar specific (Wang et al., 2015). This study found that with low permeability MAP liners, cherries accumulated high levels of ethanol, whereas high permeability MAP liners produced a fermentative off-taste after 4-6 weeks, demonstrating the importance of optimal gas transmission rates in maintaining produce.

For fresh-cut produce, active MAP did not improve shelf-life and quality of crisphead lettuce (Mattos et al., 2013) when compared to passive MAP. Although low  $\text{O}_2$  regimes reduced browning of fresh-cut iceberg lettuce, it also increased the risk of survival and growth of *Listeria monocytogenes* (O'Beirne et al., 2015). Similarly, inconsistent results were obtained for MAP fresh-cut capsicum (Rodoni et al., 2015), where raised  $\text{CO}_2$  levels caused

physiological injury. Other MAP applications have proven successful for both broccoli and lettuce (Clarke, 2011). Therefore success will be more likely if both the MAP design and environment are optimized.

There is therefore considerable scope for improvements in controlling MAP O<sub>2</sub> and CO<sub>2</sub> transmission rates, and while these can be optimized by altering film perforation and thickness (Elwan et al. 2015, Serrano et al., 2006), the structures of conventional polymers have a limited ability to maintain ideal gas compositions. In such cases, innovations in packaging technology and postharvest technologies complementary to MAP are required.

### **3. Recent Innovations in MAP Technology and Packaging**

Innovations in MAP technology (Table 1) and combinations with technologies complementary to MAP may allow for its wider use for fresh fruits and vegetables. Many of these new innovative technologies are reviewed below.

#### **3.1 New structural polymers**

Polymers that have been commonly used in MAP of fresh produce include low density polyethylene (LDPE), frequently in combination with ethylene-vinyl acetate (EVA), and other polymers derived from petrochemicals (Robertson, 2012). New structural polymers for fresh produce include linear low density polyethylene films catalyzed with metallocenes to produce films with improved structural properties and increased clarity (Robertson, 2012). Sea buckthorn was successfully preserved in a film with metallocene, aiding in the maintenance of berry structure and weight (Li et al., 2015).

New polymer trends in MAP innovation include a move towards bio-based and bio-degradable, sustainable packaging materials such as polylactic acid (PLA) (Ramos et al., 2014; Mistriotis et al., 2016), polylactide aliphatic copolymer (CPLA) (Siracusa et al., 2008), and polymers derived from high proportions of recycled plastics (Farris et al., 2009). PLA was observed to retain more red onion volatile compounds than polyethylene (PE) which is considered a lower barrier to migration of key flavor compounds (Forney et al., 2012). Apart from its high cost, the feasibility of bio-based polymers have been limited due to its poor technical performance. However, incorporation of nanotechnology within the polymer blends has greatly improved the structure and permeability properties of bio-based polymers (Fortunati et al., 2013; Peelman et al., 2013). With improved structure and functionality, and the decreasing cost of this technology, polysaccharide based bio-polymers have the potential to increase packaging sustainability (Ferreira et al., 2016).

### **3.2 New thermoresponsive functionality**

A major issue for effective control of MAP is the high dependence of respiration on temperature. Although cold chain technologies are used to reduce respiration and microbial growth, product on retail display or post purchase by the consumer can be subjected to temperature abuse. New improved polymer technologies are therefore being developed to allow for greater control over gas composition under changeable temperature conditions. For example, BreatheWay® is a membrane containing thermoresponsive crystalline polymers designed to respond to changes in temperature by allowing for higher gas transmission rates at higher temperatures. This technology has been shown to preserve optimal gas compositions over a wider range of temperature conditions for broccoli and iceberg lettuce (Clarke, 2011). It has also been shown to reduce ascorbic acid loss, maintain key flavors and

keep brighter color in MAP cherries more successfully than conventional MAP technologies (Wang et al., 2015).

### **3.3 Nanotechnology functionality**

There is growing interest in the use of nanotechnology to enhance the functionality of packaging for fresh fruits and vegetables (Table 2). Nanoparticles can invest films with key antimicrobial, structural and barrier properties (Eleftheriadou *et al.* 2017). Nanotechnology can also increase the strength and mechanical properties of films (Ramos et al., 2014), and reduce their O<sub>2</sub> transmission rates (Fortunati et al., 2013).

For whole produce, packaging with antimicrobial compounds such as nano-titanium dioxide and nano-argentum (silver) inhibited fruit respiration and decay in Chinese bayberry (Wang et al., 2010), while chitosan coatings containing a nano-emulsion of mandarin essential oil aided in the preservation of green beans when combined with both high pressure and pulsed light processing treatments (Donsì et al., 2015).

For fresh-cut produce, nano-zinc oxide inhibited ethylene production in fresh-cut apples (Li et al., 2011), silver nanoparticles embedded in SiO<sub>2</sub> and TiO<sub>2</sub> carriers demonstrated antimicrobial activity in packaged fresh-cut carrots (Becaro et al., 2015), and nano-CaCO<sub>3</sub> packaging inhibited browning of fresh-cut yams (Luo et al., 2015).

Consumers however, have expressed concerns on the possible adverse health or environmental effects with the use of nanotechnology in food packaging. This includes fears of potential contamination of foods from the release of substances such as silver via migration from packaging (Su et al., 2015). Unless addressed, these concerns may restrict the widespread adoption of nanotechnology in packaging.

### **3.4 Non-conventional gas compositions**

The application of gases other than O<sub>2</sub>, N<sub>2</sub> and CO<sub>2</sub> for improving MAP has been extensively researched. Enriching the atmosphere of packaging environments with noble gases has been successfully trialed for fresh produce (Char et al., 2012; Wu et al., 2012; Silveira et al., 2014). Elevated levels of argon (95%) extended the shelf-life of watercress (Pinela et al., 2016), and prevented color change in rocket leaves (Baldassarre et al., 2015). High concentrations of argon (90%) inhibited mold growth in fresh-cut apple (Pardilla et al., 2013), and xenon increased the shelf-life of asparagus and cucumber, but the commercial viability of these gases may be limited by its high costs (Zhang et al., 2008; Artés et al., 2009).

In general, the efficacy of non-conventional gases has been suggested to be related to their ability to lower the water activity of the packaged food (Caleb et al., 2013). Additionally, argon was shown to extend shelf-life by interfering with oxygen receptor sites of enzymes (Char et al., 2012). Helium increased O<sub>2</sub> diffusion, which, in turn, decreased the concentration gradient between the interior and exterior of cells, minimizing the potential for anaerobic fermentation and allowing storage of produce in very low O<sub>2</sub> conditions (Robles et al., 2009). Earlier trials of other noble gases such as krypton and neon (Ben-Yehoshua et al., 1993) no longer appear to be under serious commercial consideration.

In addition to noble gases, the efficacy of MAP has been improved by manipulating O<sub>2</sub> levels in nonconventional ways. High O<sub>2</sub> compositions successfully reduced browning and the development of anaerobic spoilage in eggplant (Li et al., 2014b). Packaged sweet cherries flushed with super atmospheric O<sub>2</sub> (100 kPa) reduced ethylene production and extended shelf-life greater than those packaged with air, high CO<sub>2</sub> or N<sub>2</sub> (Wang et al., 2014). The

effectiveness of high O<sub>2</sub> has been shown to be strongly dependent on the type of produce, and the temperature and length of storage (Kader and Ben-Yehoshua, 2000; Ghidelli et al., 2015).

### **3.5 Non-conventional storage temperatures**

The application of temperature treatments outside of conventional cold chain conditions has also been researched. MAP with storage at subzero temperatures has the potential to greatly increase the potential shelf-life of fruits and vegetables that are not susceptible to chilling injuries. Subzero temperatures increased the storage life of MAP fresh vegetables such as turnips and swedes (Helland et al., 2016a) and fruits such as figs (Villalobos et al., 2016). Exploiting the gap between the freezing point of water and the ice crystallization point in produce through a process known as “super-cooling” can increase the shelf-life of a wide range of fruits and vegetables (James et al., 2011), and its combination with MAP could be a valuable future development in packaging technology.

## **4. Innovative Packaging Technologies Complementary to MAP**

New food preservation technologies are emerging that have the potential to combine with MAP to considerably extend shelf-life and maintain quality of fresh fruits and vegetables. Active packaging MAP — where there is an interaction between food, packaging film and the environment — and intelligent packaging MAP — where food quality is monitored inside the packaging — are two new concepts used increasingly in food packaging innovation (Dobrucka and Cierpiszewski, 2014; Biji et al., 2015).

#### **4.1 Active packaging**

Active packaging refers to packaging that is designed to absorb or release bioactive compounds from or into the package environment and thus provide a mechanism for improved preservation of produce. In MAP, this can be achieved by flushing pre-set gas mixtures into the package, allowing for the ideal gas equilibrium to be achieved earlier than passive MAP techniques (Banda et al., 2015; Helland et al., 2016b). Other methods include the use of scavengers and absorbers to achieve the desired packaging conditions. For fresh produce, the most commercially important form of active packaging are small sachets of oxidizable iron based compounds used as O<sub>2</sub> scavengers (Kartal et al., 2012), which can prevent fruit discoloration and minimize chilling injuries (Ferreira et al., 2012). O<sub>2</sub> scavengers and absorbers have proven to be especially effective for reducing spoilage of oxygen sensitive fruit such as strawberries (Aday and Caner, 2013). Similarly CO<sub>2</sub> scavengers, such as calcium hydroxide, are increasingly being used in fresh produce packaging to delay senescence, and reduce browning and mould incidence (Lee, 2016).

1-methylcyclopropene (1-MCP) is a compound that antagonizes ethylene by interacting with hormonal receptors in fruits and vegetables to prevent ethylene action. 1-MCP can delay ripening processes in climacteric fruits (Vanoli et al., 2016) and has considerable use in long term cold storage of pome fruit (Georgoudaki and Nanos, 2015). 1-MCP is increasingly being combined with MAP for other ethylene sensitive fresh produce (Li et al., 2016), and has also been shown to slow down senescence, color change and degreening in non-climacteric fruits (Li et al., 2016). 1-MCP is effective at very low concentrations, is non-toxic, and is widely available commercially (Vázquez-Celestino et al., 2016), so could potentially be used with a wide range of fresh fruits and vegetables. Other technologies, such as potassium permanganate, actively oxidize or absorb ethylene (Wills, 2015), and are beneficial for fruits

such as strawberry whose metabolic pathways are negatively affected by 1-MCP (Ku et al., 1999).

Other new active packaging technologies include absorbent trays and pads to remove excess fluid from fresh-cut produce (Bovi et al., 2016), antioxidant films to minimize oxidation reactions (Wrona et al., 2015), filter papers with additives such as vanillin and cinnamic acid known for their antimicrobial properties (Silveira, 2015), and ethanol vapor sachets that have been successfully trialed to enhance berry color and reduce fungal decay of table grapes (Candir et al., 2012). Film with antifog properties delayed senescence and loss of pigment stability for green chilies (Chitravathi et al., 2015a).

#### **4.2 Edible coatings**

Edible coatings and films are considered a subset of active packaging (Table 3). Given that they are both a packaging and a food component, the ideal edible coating should satisfy a range of requirements: good sensory attributes, high barrier and mechanical properties, biochemical physicochemical and microbial stability, simple technology and low raw material and processing cost, as articulated in recent reviews (Dhall, 2013; Corbo et al., 2015). Recent advances in the incorporation of antimicrobial components into edible coatings is increasing their utility and use (Dhall, 2013).

Edible coatings can be derived from a wide range of plant and animal sources (Dhall, 2013). Chitosan, derived from shellfish and arthropod waste, has become a common starting material for edible films and coatings in fresh fruits and vegetables. It has wide ranging antimicrobial properties (Leceta et al., 2015), and good film-forming characteristics (Pushkala et al., 2013). Chitosan can be mixed with very low cost materials such as banana flour to reduce costs without any loss in antimicrobial effectiveness (Pitak and Rakshit,

2011). The antimicrobial activity of chitosan films has been increased by the addition of other antimicrobial agents such as benzoic acid and ascorbic acid, both in normal and nano-sized forms (Cruz-Romero et al., 2013). Edible coatings based on plants materials such as xanthan gum and tapioca starch, have also shown to increase the shelf-life and quality of fresh produce (Galindo-Pérez et al., 2015; Pan et al., 2013). For example, a formulation of lactic acid, citric acid, lemongrass essential oil and Tween 80 preserved the sensory qualities of pre-cut cauliflower while significantly decreasing microbial load (Boumail et al., 2016). Similarly, ascorbic and citric acid in edible films reduces browning and therefore maintain color of fresh-cut mango stored over 12 days (Robles-Sánchez et al., 2013).

Recent studies have shown the potential to combine the benefits of edible coatings and MAP. MAP and a soy protein based edible coating helped maintain the anti-oxidant capacity of fresh-cut artichokes (Ghidelli et al., 2015). In contrast, an edible coating derived from chitosan, pectin and sodium caseinate, by itself did not significantly affect quality parameters (total soluble solids, acidity, browning index) of fresh-cut nectarine (Ramirez et al., 2015). However, when the edible coating was combined with MAP, shelf-life was extended to 7 days. Similar results were also found with eggplant, with shelf-life extended to 9 days using a soy protein-cysteine based edible coating (Ghidelli et al., 2014). These results suggest that a combination of MAP with edible film technology could become an important approach in the packaging of fresh fruits and vegetables.

Food producers have shown reluctance to transition from petrochemical derived plastic polymers to using edible coatings. This is due to concerns over costs and over performance, particularly in relation to shelf-life and durability of the edible films (Robertson, 2012). However, the development of new superior sources of coatings with durability could increase their widespread commercial adoption.

### **4.3 Intelligent packaging**

Intelligent packaging, also known as smart packaging, describes packaging incorporated with sensors to monitor the quality, safety, temperature, movement and condition of foods along the supply chain (Kuswandi et al., 2011; Jedermann et al., 2014). Recent examples, including radio frequency identification sensors, ripeness indicators and biosensors, are reviewed by Meng et al. (2014). Intelligent packaging can communicate both food safety and quality, or measurements that are indicative of these concepts (Toivonen et al., 2014), and could be a point of difference utilized in innovative packaging designs. Meng et al. (2014) suggested that the emerging consumer preferences for modern food safety technologies has promoted the growth of intelligent packaging.

There exists a range of low cost intelligent packing options that provide visual information on the state of freshness. Fluorescent dyes incorporated within the packaging that can signal increases in O<sub>2</sub> are a common method for optical detection of changes in gas composition (Hempel et al., 2012) as reviewed by Puligundla et al. (2012). Molybdenum ions changed color in the presence of ethylene which corresponded with ripeness factors in apples (Lang and Hübner, 2012), while bromophenol blue changed color with excess production of organic acid, indicating over-ripeness in guava (Kuswandi et al., 2013). Dyes that correspond to changes in CO<sub>2</sub> concentration have been incorporated into chitosan coatings for kimchi (Meng et al., 2015), and the possibility exists for trialing this technology in coatings of fresh produce as well.

#### **4.4 Packaging functionality**

The functionality of packaging is arguably maximized when packaging contains and protects products, while offering optimal convenience to consumers (Robertson, 2012). Improving packaging functionality is a rapidly evolving space in industry. However, there is little peer-reviewed literature on the efficacy of these technologies.

New innovations are constantly emerging in fresh produce packaging, as new advances allow for the design of packaging to play a greater role in protecting and preserving produce. Pact Group have developed Shocksorb® protective trays, replacing bubble wrap in packaging for delicate fruit, and Moisturelock® absorbent packaging, to replace moisture pads for bleeding fruits such as berries.

Some fruits and vegetables are highly susceptible to mechanical and vibrational damage, and new packaging technology has been found to aid in preventing produce deterioration. Key influences on mechanical damage of packaged produce include the position of the produce within the package, the contact between individual produce items, and the ability of the package itself to absorb mechanical effects (Fadiji et al., 2016).

Convenient packaging reduces food loss and waste through moderating portion size and easing handling operations (Wikström et al., 2014; Verghese et al., 2015). Through influencing portion control, producers can sell portions of fresh produce suitable for individual or multiple consumers, also allowing for rapid and easy preparation of meals.

For fresh-cut products, new services giving consumers or food retailers set amounts of pre-cut ingredients in separate packaging may also reduce food waste by minimizing cross-contamination and spoilage (Sand, 2015). Resealable packaging allows for greater and more affordable serving sizes without increasing food waste due to unused produce decaying,

maximizing the shelf-life of a product (Ferreira et al., 2016) and increasing consumer desirability (Jinkarn and Suwannaporn, 2015).

#### **4.5 Complementary post-harvest technologies**

Current MAP systems alone may not be adequate for effectively preventing deterioration, and slowing microbial growth in fresh produce (Nicola and Fontana, 2014) or fully addressing the additional challenges for preservation of fresh-cut produce. Recent research has therefore focused on examining the potential synergistic effects of MAP when combined with another or even multiple post-harvest sanitation technologies (Table 4).

UV-C treatments in combination with MAP slowed post-harvest senescence of rocket (Gutiérrez et al., 2015), maintained overall fruit and vegetable quality of watermelon and broccoli (Artés-Hernández et al., 2010; Martínez-Hernández et al., 2013), while UV-C treated pineapple was preferred by consumers to control samples (Manzocco et al., 2016). Effective treatments ranged from 0.2 to 6.0 kJ m<sup>-2</sup> UV-C with packaging exposed to UV light requiring to be made of polymers capable of transmitting UV beams (Novák et al., 2016).

For highly perishable products such as fresh-cut products, irradiation in combination with MAP has been suggested as a useful way to slow deterioration rates (Simko et al., 2015). Low dose irradiation (0.6 kGy) has been successfully used for packaged fruit, such as blueberry and cherry (Thang et al., 2016), and doses of 1 kGy have effectively preserved MAP watermelon suitable for use in refrigerated vending machines (Smith et al., 2017). Packaging to be irradiated must be manufactured from a polymer capable of withstanding material degradation (Novák et al., 2016).

Novel gas treatments prior to MAP could become a useful tool for extending produce shelf-life. Exposing asparagus to extreme O<sub>2</sub> deprivation (anoxia) prior to MAP lowered respiration rate, slowing the reduction of sugar and ascorbic acid levels (Techavuthiporn and Boonyaritthongchai, 2016). Exposing cherry tomatoes to 20% and 60% CO<sub>2</sub> levels for 3 hours before storage at 12°C increased the tartaric content compared with tomatoes exposed to air (Sangwanangkul et al., 2017), and similar treatments may be useful to replace or complement MAP. Hydrogen sulfide gas can act as a signaling regulator in plants to delay the postharvest senescence of broccoli in a dose-dependent manner (Li et al., 2014a). Following exposure to this gas, broccoli was shown to maintain higher levels of secondary metabolites, such as carotenoids, anthocyanin, and ascorbate, while down-regulating chlorophyll degradation related genes. Hydrogen sulfide gas released from sodium hydrosulfide has also been demonstrated to inhibit fungal growth on fresh-cut pears (Hu et al., 2014), and future trials could investigate its effectiveness in combination with MAP.

Other technologies that have increased the efficacy of MAP include dipping treatments with natural antimicrobial products such as citral and carvacrol (Siroli et al., 2014), ascorbic acid (Li et al., 2014) and calcium lactate (Cefola et al., 2014). Ozone and chlorine wash sanitation treatments have been combined with MAP to successfully extend the shelf-life of green chilies (Chitravathi et al., 2015b). Similarly, ozone treatments combined with MAP extended the shelf-life of ready-to-eat capsicum strips (Horvitz and Cantalejo, 2015). Heat treatments (55 °C for 45 s) combined with MAP reduced browning and increased the shelf-life of fresh-cut lotus root (Son et al., 2015). Prior treatment with neutral electrolyzed water (NEW) enhanced the shelf-life of MAP fresh-cut lettuce (Posada-Izquierdo et al., 2014).

## **5. Conclusion**

With global demand growing for fresh and particularly for minimally processed and fresh-cut produce, new and improving technologies will be required to preserve fruits and vegetables for longer duration while retaining their quality. While much is known on the benefits derived from MAP for preserving many important fruits and vegetables, new innovations in packaging and complementary post-harvest technologies to improve shelf-life and quality retention are still needed to meet consumer expectations.

Small reductions in the use of food packaging materials can lead to large cost savings for producers, as well as significant reductions in waste. Both consumer preferences and government initiatives are driving the move towards more efficient and less wasteful packaging technologies. Important innovations could come from the re-use of packaging, packaging that requires less raw materials, and the use of eco-friendly raw materials where possible. Packaging designs that reduce food waste are also being investigated, and improvements in this area will be necessary to significantly lessen waste associated with food packaging.

The use of sensors in intelligent packaging, already widespread in many cooked and processed products, is increasingly being found in fresh produce applications. This could help producers, retailers and consumers make informed choices about food quality and freshness.

Additional studies are needed on consumer perceptions of the effect of MAP on quality of fruits and vegetables over time. While many studies have evaluated food safety effects of MAP, less work has been conducted on its effects on consumer acceptability and perceived freshness and convenience. There is also uncertainty about how consumer respond to additional information provided by intelligent packaging sensors incorporated into package marketing.

New packaging materials are being trialed, particularly bio-based and bio-degradable polymers. By incorporating nanotechnology, modern bio-polymers should overcome structural weaknesses present in some older bio-derived plastics. Similarly, nanotechnology is being used to incorporate materials such as copper into films to invest antimicrobial and ethylene control properties. Perforation, thickness and polymer type can all play crucial roles in the effectiveness of MAP, and choosing the correct MAP type can significantly enhance fruit and vegetable quality and shelf-life.

## Acknowledgements

This work was supported by the Australian Research Council's Industrial Transformation Training Centres scheme under Grant IC140100024.

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**Table 1. Recent reported uses of novel packaging technologies with fresh produce**

Technology	Company	Produce type	Novel aspect	Reference
Active trays	Artibal	Peach	Label with cinnamon essential oil	Montero-Prado et al. (2011)
Antimold® ethanol vapor sachet	Freund	Table grape	Ethanol vapor generating sachet to reduce fungal decay	Candir et al. (2012)
Antioxidant packaging	Artibal	Fresh mushroom	Active coated polyethylene packaging	Wrona et al. (2015)
BreatheWay®	Apio	Sweet cherry	Thermoresponsive crystalline polymers	Wang et al. (2015)

Dri-Fresh® Resolve® absorbent pads	Sirane	Melon, kiwi fruit	Cellulosic absorbent membrane pads	Lloret et al. (2012)
Freshness indicator	ripeSense ®	Guava	Label changes color to indicate freshness	Kuswandi et al. (2013)
Fresh-R-Pax® absorbent pads	Maxwell Chase	Fresh-cut tomato	Sodium carboxymethyl cellulose pads	Ahmed et al. (2012)
Oxyfree® 504 oxygen absorber	O-Buster	Scarlet eggplant ( <i>Solanum gilo</i> )	Oxygen absorbing sachet	Ferreira et al. (2012)
PrimePro® ethylene remover	Chantler	Sweet cherry	Proprietary active packaging liner	Wang et al. (2015)

**Table 2. Recent reported uses of nanotechnology to enhance the functionality of packaging materials**

Nanotechnology type	Polymer type	Functionality	Produce applications	Reference
Cellulose nanocrystals, silver nanoparticles	PLA	↑ barrier performance against O <sub>2</sub> , water vapor and light	Fresh-cut melon and kiwifruit	Lloret et al. (2012); Fortunati et al. (2013)
Thymol and modified montmorillonite	PLA	↑ mechanical properties, ↓ glass	Not given	Ramos et al. (2014)

Nanoemulsion of mandarin essential oil	Chitosan	↑ transmission temperature ↑ antimicrobial activity	Green beans	Donsì et al. (2015)
Silver nanoparticles	LDPE	↑ antimicrobial activity	Fresh-cut carrots	Becharo et al. (2016)
Titanium oxide nanocomposite	LDPE	↑ antimicrobial activity	Pears	Bodaghi et al. (2013)
Nano-calcium carbonate	LDPE	↑ retention of fruit quality	Fresh-cut Chinese yam	Luo et al. (2015)
Montmorillonite	Edible film	↓ water vapor permeability	Acerola	Azeredo et al. (2012)
Nanofibrillated cellulose	Biocomposite film	↓ water vapor permeability	Not given	Sirviö et al. (2014)

**Table 3. Recent examples of edible coatings for fresh fruits and vegetables**

Edible film	Uses	Whole (W) or fresh-cut (F)	Functionality	Reference
Chitosan	Baby carrot	W	Retained positive color and texture	Leceta et al. (2015)
Antimicrobial enriched	Broccoli	F	Improved microbial control of chitosan	Alvarez et al. (2013)

Essential oil enriched	Green bean	W	Improved microbial control of chitosan	Donsi et al. (2015)
Alginate	Pineapple	F	Greater shelf-life and quality retention	Azarakhsh et al. (2014)
<i>Aloe arborescens</i>	Peach, plum	W	Delayed color change. Reduced weight loss	Guillén et al. (2013)
<i>Aloe vera</i>	Kiwifruit	F	Extended shelf-life while maintaining sensory properties	Benítez et al. (2015)
Banana flour (in composite with chitosan)	Asparagus, baby corn, Chinese cabbage	F	Protected against <i>S. aureus</i> activity	Pitak and Rakshit (2011)
Carboxymethyl cellulose	Apple	F	Combined with ascorbic acid dips to reduce browning	Koushesh Saba and Sogvar (2016)
Cassava starch	Apple	F	Combined with essential oils to inhibit microbial growth	Oriani et al. (2014)
Fruit and vegetable residue flour	Acerola	W	Reduced weight loss	Ferreira et al. (2015)
Gum arabic enriched with calcium chloride	Mango	W	Reduced chilling injury and electrolyte leakage	Khaliq et al. (2016)
Soy-based	Artichoke	F	Combined with MAP to maintain	Ghidelli et al. (2015)

Tapioca starch with cinnamon oil	Apple	F	antioxidant capacity Reduced microbial growth and ethylene production	Pan et al. (2013)
Xanthan gum with nanocapsules	Apple	F	Decreased respiration rate by 63%	Galindo-Pérez et al. (2015)

**Table 4. Recent reported uses of complementary technologies with fresh produce in modified atmosphere packaging**

Technology	Produce type	Whole (W) or fresh-cut (F)	Functionality	Reference
Antimicrobial dips	Apple, eggplant, nectarine	F	Reduced biological and biochemical deterioration	Cefola et al. (2014); Li et al. (2014b); Siroli et al. (2014)

Chlorine wash	Green chili	W	Extended shelf-life by 6 days	Chitravathi et al. (2015b)
Electrolyzed water	Lettuce	F	Extended shelf-life stored at 8°C	Posada-Izquierdo et al. (2014)
Irradiation	Blueberry, cherry	W	Suitable for phyto-sanitary treatment. Did not affect shelf-life	Thang et al. (2016)
Ozone	Green chili	W	Extended shelf-life by 14 days	Chitravathi et al. (2015b)
UV-C	Watercress	W	Reduced <i>E. coli</i>	Hinojosa et al. (2015)

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