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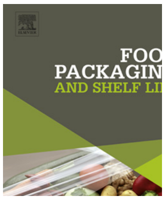

Perforation-mediated modified atmosphere packaging of fresh and minimally processed produce—A review

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ABSTRACT

The overwhelming global demand by consumers for convenience and fresh quality fruit and vegetables, heightens the need for appropriate postharvest technologies. In order to maintain freshness quality attributes, extend the shelf life of fresh/minimally processed produce and reduce postharvest losses. Perforation-mediated modified atmosphere packaging (PM-MAP) offers the benefit of avoiding in-package anaerobiosis, extending the shelf life and maintaining quality fresh or minimally processed produce. This article presents an overview on the role of postharvest hurdle technologies in food packaging, critical evaluation of MAP and PM-MAP dependent parameters and the role of mathematical models. Furthermore, the successful application of PM-MAP on fresh and minimally processed produce was highlighted and future research prospects and challenges were identified.

Contents

1. Introduction

Fruit and vegetables are a rich source of micronutrients, fibres, vitamins and remarkable content of phytochemicals (with antioxidant properties) such as anthocyanins, carotenoids, polyphenols and

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flavonoids. This makes them essential components of the daily human diet (Allende, Tomas-Barberan, & Gil, 2006; Opara & Al-Ani, 2010; Rico, Martn-Diana, Barat, & Barry-Ryan, 2007). Consumption of fresh fruit and vegetables is associated with a number of nutritional and health benefits. It is highly recommended as health diet to fight against sedentary life style and degenerative diseases such as cancer, cardiovascular diseases and ageing (Allende et al., 2006; Rico et al., 2007; Ramos, Miller, Brandão, Teixeira, & Silva, 2013). Over the last decade, there has been a rapid expansion of fresh and minimally processed produce industry with multiple digit growth (Allende, Luo, McEvoy, Artés, & Wang, 2004; Montanez, Rodriguez, Mahajan, & Frias, 2010; Siddiqui, Chakraborty, Ayal-Zavala, & Dhui, 2011). This has been attributed to change in consumers' life style and increase in consciousness of healthy diet, which result in high demand for healthy, fresh and ready-to-eat fruit and vegetables (Caleb, Mahajan, Al-Said & Opara, 2013a; Ramos et al., 2013; Rico et al., 2007).

One of the major challenge facing the production and marketing of fresh minimally processed produce is rapid quality deterioration and reduced shelf-life (Hussein, Caleb, Jacobs, Manley, & Opara, 2015). Life processes of fresh fruits and vegetables and fresh-cuts continue after harvest due to on-going metabolic activities including respiration and ripening which continue in cells or plant parts until senescence and death (Irtwange, 2006; Sandhya, 2010). These biological (internal) causes of deterioration lead into undesirable quality changes in harvested produce, which are characterized by changes in color, texture, flavour, and nutritive value (Kader, 2005). Additionally, rapid quality deterioration and reduced shelf life may also result from physiological disorders and presence of mechanical injuries, which represent major quality challenges for the marketing of fresh minimally processed produce (Siddiqui et al., 2011). Overall, inadequate management of these quality challenges may result in reductions in availability, edibility, quality as well as wholesomeness, contributing to the incidence of postharvest food losses and subsequent financial losses (Fallik, 2004; Irtwange, 2006; Kader, 2005; Mahajan, Caleb, Singh, Watkins, & Geyer, 2014; Opara, 2009; Opara, Al-Ani, & Al-Rahbi, 2012).

High levels of postharvest losses coupled with increasing global market demand for fresh fruits and vegetables press the need for appropriate postharvest technologies to reduce quality loss and extend shelf-life of whole fresh and minimally processed produce (Kader, 2005; Montanez et al., 2010; Opara, 2010a; Opara & Mditshwa, 2013). As one of the most promising postharvest technologies to reduce fresh food losses, researchers have examined the application of various aspects of modified atmosphere packaging (MAP) on different types of fresh produce. A good number of published reviews have addressed advancements in the use of MAP and its potential to preserve quality and extend shelf-life of fresh and minimally processed produce (Caleb et al., 2013a; Oms-Oliu, Raybaudi-Massilia, Soliva-Fortuny, & Martin-Belloso, 2008; Rojas-Grau, Oms-Oliu, Soliva-Fortuny, & Olga Martın-Belloso, 2009; Sandhya, 2010). Others have examined the influence of MAP on growth of resistant foodborne pathogens and subsequent outbreaks of foodborne diseases (Caleb et al., 2013a; Farber et al., 2003). In this review, the basic principles of MAP and parameters affecting the performance of MAP are discussed. This is followed by a detailed discussion of perforation-mediated modified atmosphere packaging (PM-MAP), including the principles, functions and applications to fresh and minimally processed produce.

2. Overview of postharvest technologies applied to reduce losses and extend shelf-life of fresh horticultural produce

The quality of fresh produce cannot be improved after harvest; nevertheless, it remains possible to slow down the rate of undesirable changes and maintain quality for a longer time (Kim, Silva, Tokitkla, & Matta, 2010). Postharvest technologies refer to various techniques applied to reduce losses, extend quality and shelf life of fresh and minimally processed produce (Opara, 2006, 2010b). In this regard, various postharvest technologies to preserve quality and extend shelf life during distribution and short-term storage of fresh and minimally processed produce have been reviewed (Mahajan et al., 2014; Ramos et al., 2013; Siddiqui et al., 2011; Soliva-Fortuny & Martin-Belloso, 2003). The use of chemical-based treatments such as washing with sanitizers, antioxidant treatments and ozonised water are among the postharvest preservation methods that have been successfully applied in the fresh fruit and vegetable industries (Francis, Thomas & O'Beirne, 1999; Garcia & Barrett, 2002; Garcia, Mount, & Davidson, 2003; Beltran, Selma, Tudela, & Gil, 2005). Furthermore, physical treatments such as application of heat (e.g. blanching, heat-shock and hot water dips) have been used to delay physiological deterioration of fresh produce such as pomegranate arils (Maghoumi et al., 2012) and citrus (Hong et al., 2014). Other physical methods include irradiation which is based on exposing food to different sources of radiant energy and ultraviolet light which have been reportedly used as antimicrobial treatments (Fallik, 2004; Hong et al., 2014; Maghoumi et al., 2012; Tahir, Johansson, & Olsson, 2009).

The application of a wide range of edible and antimicrobial coatings represents another group of important postharvest treatment technologies which have received considerable attention over the years (Bourtoom, 2008; Cagri, Ustunol, & Ryser, 2004; Dhall, 2013; Campos, Gerschenson, & Flores, 2011). Edible coatings incorporate thin layers of edible materials applied on food produce or at the interfaces between different layers of food components (Bourtoom, 2008; Falguera, Quintero, Jiménez, Muñoz, & Ibarz, 2011). Such coatings serve an important role as protection against microbial activity and oxidation, physical damage and prevention of moisture loss (Bourtoom, 2008; Falguera et al., 2011; Dhall, 2013). Smart or intelligent packaging (IP) is another interesting innovation that has gained interest in the horticultural food industry which may be designed to track produce, sense the external and internal environment of the package and communicate any changes to consumer or food manufacturer, thus monitoring the quality and safety status of produce (Caleb et al., 2013a; Yam, Takhistov, & Miltz, 2005). Intelligent packaging is also commonly referred to as 'interactive packaging' due to its ability to give information about produce quality along the chain, during transport and storage (Sandhya, 2010; Yam et al., 2005). Active packaging is another valuable technology which is characterised by the use of absorbers and emitters (or releasing systems) of active ingredients, ethylene scavengers/emitters and moisture absorbers in the package (Rodriguez-Aguilera & Oliveira, 2009). Active ingredients in an active package modify the atmosphere surrounding produce inside the package, thereby extending produce shelf-life (Vermeiren, Heirlings, Devlieghere, & Debevere, 2003). However, the practical application and widespread use of active and intelligent packaging systems is limited mainly due regulatory issues (e.g. application of antimicrobial packaging systems) and technical limitations such as high cost associated with these technologies (Realini & Marcos, 2014; Yam et al., 2005).

Increasing consumer awareness about health benefits and safety of food has driven the fresh produce industry to minimise the use of chemicals that have hitherto been commonly applied as sanitizing and preservative agents (Meyer, Suhr, & Nielsen, 2002; Ramos et al., 2013). Apart from the health concerns, it has been reported that the use of chemical sanitizers and washings cannot guarantee the microbial quality of produce without compromising sensory quality (Rico et al., 2007). As a result, most of the inorganic chemical treatments and washing sanitizers such as chlorine-based chemicals have recently faced critical challenges to gain widespread acceptance in the fresh produce industry (Meyer et al., 2002; Rico et al., 2007). Most recently, the combination of different preservation techniques (hurdle technology) as a preservation strategy has successfully been applied in controlling microbial growth and reduction of quality losses (Allende et al., 2006; Rico et al., 2007). Hurdle technology relies on various combinations of control of temperature, acidity, redox potential, water activity, and use of preservatives and modified atmospheres to delay quality deterioration. However, the selection of hurdles should be tailor-made to achieve the desired control of quality attributes of a specific produce (Allende et al., 2006). Accordingly, combining appropriately selected hurdles lowers the intensity at which each individual preservation techniques can be applied while achieving a collective action to minimise loss of quality and/or suppress microbial growth (Allende et al., 2006; Ramos et al., 2013).

2.1. Packaging films

Polymeric films are used extensively in the food packaging industry for handling fresh fruit and vegetables (Kirwan, Plant, & Strawbridge, 2011; Mangaraj, Goswami, & Mahajan, 2009; Siracusa, 2012). The reasons for their success and rapidly increasing application include their versatility which makes them easy to produce as flexible films or rigid containers of various sizes and shapes (Del-valle, Almenar, Hern, & Gavara, 2004; Kirwan et al., 2011; Siracusa, 2012). In addition, the thermosetting or thermoplastic properties provide heat sealing, transparency, excellent chemical resistance, heat resistance and good barrier properties, which are remarkably suitable for the application of advanced packaging technologies such as modified atmosphere packaging (MAP) (Kirwan et al., 2011; Lagaron, Catala, & Gavara, 2004; Mangaraj et al., 2009).

There are a variety of polymeric films used in packaging of fresh and minimally processed produce. A portion of these polymers is used in primarily flexible packaging structures, others are used in primarily rigid packaging structures, while the remainder are used in both applications. Each specific polymer has unique physical, mechanical, chemical, and gas barrier properties (Brandenburg & Zagory, 2009). Unlike glass or metallic packaging materials, polymeric films are permeable at different levels to small molecules such as gases, water and organic vapour, and to other low molecular weight compounds like aromas, flavour, and additives present into food (Mrkic, Galic, Ivankovic, Hamin, & Cikovic, 2006; Siracusa, 2012). The chemical composition and properties of plastics can be designed to provide optimum permeability to gases and water vapour to extend the shelf-life of specific fruits and vegetables (Allan-Wojtas, Forney, Moyls &. Moreau, 2008). As a consequence of the permeability properties, the barrier of films ranges from high to low (Siracusa, 2012). The degree of film permeability is crucial to maintain gas and moisture composition within the package (Del-valle et al., 2004; Kirwan et al., 2011). Additionally, the manufacturing, handling, and package engineering operations can influence the final properties of packaging films (Gajdoš, Galic, Kurtanjek, & Cikovic, 2000; Mrkic et al., 2006; Siracusa, 2012).

Flexible plastic packaging films accounts for about 90% of the materials used in MAP of fruit and vegetables, while paper, paperboard, aluminium foil, glass and metal containers accounts for the remainder (Mangaraj et al., 2009). These materials have been reported to provide a wide range of permeability to gases and water vapour, which is essential for the success of MAP technology. Advancements in polymer engineering have enabled the combination of various packaging materials with different polymeric properties. Techniques such as co-extrusion, lamination and coating have led to the development of different packaging formats in the market, ranging from flexible bags, pouches, pillow packs and top webs in sealed tray systems to rigid and semi-rigid structures for base trays, dishes, cups and tubs (Mangaraj et al.,

Table 1
A summary of benefits and drawbacks of polymeric films commonly used in food packaging.
Blakistone (1999); Kirwan et al. (2011); Mullan and McDowell (2011).

Polymeric film	MAP use suitability	
	Benefit properties	Drawbacks
Polyvinylidene chloride (PVdC)	Good heat sealabilty that provide peelable feature of MAP Excellent gas, dour and water barrier properties Good resistance to oil, grease and organic solvents Excellent heat sealabilty (able to seal to itself and to other materials)	High barrier to water vapour and gases limit is use for MAP of high respiring produce
Linear low density polyethylene (LLDPE)	Good sealing quality, and therefore its application on the sealing face allows a peelable seal to be made Used as a sealant layer on base trays and lidding films	
Polyvinyl alcohol (PVOH)	Good barrier properties against WV and oxygen (when used properly). It can be copolymerised with ethylene to produce EVOH with improved WV permeability	Barrier properties are moisture-dependent
Bi-axially oriented polypropylene (BOPP)	Rigid and hard plastic material. Being bi-axially oriented, it has improved tensile strength and hence useful as a base tray. Good barrier to water vapour and gases	Higher barrier water vapour limits its suitability to MAP of some fresh produce
Polyamide	Good barrier to gas, flavour, odour loss. High resistance to stress cracking and puncture High water vapour permeability	Not suitable for MAP of high respiring produce Tends to absorb moisture from their environment
Ethyl vinyl alcohol (EVOH)	Excellent barrier to oxygen thus used as a gas barrier layer in MAP applications Barrier to the absorption and permeation of oil, fat and sensitive aromas and flavour Good processing properties	Less sensitive to the presence of moisture Not suitable for MAP of high respiring produce
Polystyrene (PS)	Stiff and brittle material with high gas permeability Foamed PS used as structural layer for preformed MAP base tray applications	Cannot be used alone in MAP application due to high gas permeability, unless combined with EVOH
Polyvinyl chloride (PVC)	Has low softening temperature, good processing properties, thus suitable material for producing thermoformed packaging structures. Excellent oil and grease resistance Common structural material in MAP thermoformed base trays	Unplasticised PVC has moderate gas and water vapour barrier properties, thus not suitable as film for MAP of high respiring produce
Ethylene Vinyl acetate (EVA	Excellent heat-sealing properties Useful as heat seal layer in some MAP applications	
High Density Polyethylene (HDPE)	Tough and stiff material Commonly used for rigid and semi-rigid structures	

2009; Mullan & McDowell, 2011; Silva, Chau, Brecht & Sargent, 1999a). Consequently, these advances have led to the availability of a wide range of packaging formats for fresh and minimally processed produce (Brandenburg & Zagory, 2009; Farber et al., 2003; Mangaraj et al., 2009).

There are numerous requirements that influence the choice of packaging films for MAP applications. These include sealing reliability (the ability to seal to itself or to other material by heating), mechanical strength, clarity, durability, resistant to chemical degradation, non-toxic and chemical inertness, printability, and commercial suitability (Kirwan et al., 2011; Lange, 2000; Mangaraj et al., 2009). Table 1 presents a summary on the properties of different polymeric films used in food packaging, with highlights on their drawbacks and benefits.

2.2. Transport properties of polymeric packaging films

Preservation of quality and safety of fresh and minimally processed packaged produce requires selection of the most appropriate packaging materials in addition to the requirements listed in Table 2. Packaging films are expected to influence the movement of respiratory gases, and therefore their relative permeability to gases is very essential (Scetar, Kurek, & Galic, 2010). In MAP of fresh and minimally processed produce, a dynamic alteration of gases within a package relies on the interplay of produce respiration rate (RR) and film permeability properties to slow down the produce RR and deterioration (Mahajan, Oliveira, Montanez, & Frias, 2007). Based on this relationship, knowledge of the gas transport properties and water vapour transmission rate (WVTR) of the packaging material is an essential criteria for the choice of film suitable for MAP (Kirwan et al., 2011; Mangaraj et al., 2009).

Barrier properties of a packaging material to gases (CO_2, O_2) or water vapour is measured by the transmission rate, which is defined as the quantity of gas or water vapour passing across a film of known area over a given time (Mullan & McDowell, 2011; Siracusa, 2012). Permeability of most common plastic polymers is affected by temperature of the surrounding, and therefore, transmission rate values are often reported for specific temperature ranges (Mullan & McDowell, 2011; Siracusa, Rocculi, Romani, & Dalla Rosa, 2008). Permeability coefficient of a packaging polymer, which relates film thickness and driving force, is a useful parameter that permits the comparison of barrier properties of different packaging films (Mullan & McDowell, 2011). Generally, a packaging film with a low oxygen permeability coefficient has a potential to extend the shelf life of packaged produce because the oxygen pressure inside the package drops hence retarding the oxidation activities (Siracusa, 2012). Similarly, the water vapour barrier of films is quantified by the water vapour permeability coefficient which indicates the amount of water vapour that permeates per unit of area and time through a packaging material, usually reported as water vapour transmission rate (WVTR) (Siracusa, 2012). Packaging plays a crucial role in reducing water loss of fresh produce by maintaining desirable humidity in the headspace atmosphere (Opara & Mditshwa, 2013; Techavises & Hikida., 2008). Excessive in-package humidity may promote food spoilage, such as development of spoilage microorganisms and decay (Mistriotis, Giannoulis, Giannopoulos, 2011). Therefore, the water vapour barrier properties of a packaging film are of great importance in extending the shelf-life of packaged produce (Del Nobile, Licciardello, Scrocco, Muratore, & Zappa, 2007).

In conventional, non-perforated polymeric films, the flow of gases across a barrier film increases with increasing concentration gradient between the package headspace and surrounding environment (Mir & Beaudry, 2004; Mullan & McDowell, 2011). This gradient creates the driving force for gas diffusion through the polymeric film produced by the reduced O_2 and elevated CO_2 resulting from the actively respiring produce (Mir & Beaudry, 2004). Equilibrium levels of O_2 and CO_2 are finally achieved in the package when the rates of O_2 uptake and CO_2 production by the packaged produce are equal to that permeating through the film, a situation favoured by steady-state (constant) RR (Caner, Aday, & Demir, 2008; Mir & Beaudry, 2004). The diffusion rates of CO_2 and O_2 through perforated and non-perforated polymeric films differ significantly (Mir & Beaudry, 2004). For non-perforated film, diffusion rate of CO_2 is between 2 and 8 times faster than O_2 (Mir & Beaudry, 2004; Scetar et al., 2010). This gives a wide range of permeability ratios of CO_2TR to O_2TR (referred to as β), which are always higher than the recommended optima values for most fresh produce (Al-ati & Hotchkiss, 2003; Mahajan et al., 2007; Šcetar et al., 2011). Due to unequal permeability rate between O_2 and CO_2 of most of commercially available films, their β values lie within a range of 2.2–8.7 (Mahajan et al., 2007). Such low O_2 and /high CO_2 permeability is undesirable for suitable application in the MAP of most minimally processed produce that require the selected film to match their high respiration rates (RRs) (Mahajan et al., 2007).

Despite the foregoing advantages, the application of polymeric films in some packaging applications such as MAP has limitations including: 9i) unpredictable changes in film permeability characteristics when stretched or punctured; (ii) relatively high barriers to water vapour, causing condensation inside packages, especially under fluctuating temperature conditions which promote the development of optimal conditions for microbial growth; (iii) non-uniformity in permeation characteristics of films that may cause

Table 2
Factors and related variables involved in the design process of PM-MAP system.
Adopted from Mahajan et al. (2007).

Factors	Variables	Designation
Extrinsic factors	Film thickness	E
Package-related	Film surface area for gases exchange	A
	Volume of the package	V
	Number of micro perforations	n
	Diameter of micro perforation	D
	Film permeability	PO_2, PCO_2
Surrounding-related	Gas composition	yO_2^{in}, yCO_2^{out}
	Temperature	T
	Atmospheric pressure	P
Intrinsic factors (produce-related)	Produce mass	M
	Produce density	ρ
	Respiration rate	RO_2, RCO_2
	Desired equilibrium gases composition	yO_2^{eq}, yCO_2^{eq}

gas stratification; (iv) higher permeability to CO_2 than O_2 of most films, which is unfavourable for high respiring products such as strawberries, grapes, citrus, mushrooms, broccoli and asparagus, and, (v) high ratio of CO_2 to O_2 permeability coefficients which is not suitable for products requiring high CO_2 and low O_2 concentrations due to increased risk of anaerobiosis (Fonseca, Oliveira, Lino, Brecht, & Chau, 2000; Oliveira, Fonseca, Oliveira, Brecht, & Chau, 1998). Due to these limitations, it is known that polymeric films may generate in-package atmospheric conditions outside the ideal optimal requirements for most fresh produce (Lee & Renault, 1998; Mahajan et al., 2007; Mahajan, Rodrigues, & Leflaive, 2008). For these reasons, there is the need to optimize the application of MAP for preserving highly respiring produce and should be product specific.

3. Perforation-mediated modified atmosphere packaging (PM-MAP)

3.1. Importance of PM-MAP

Permeability properties of most polymeric films commonly used in MAP represents an important limitation, for highly respiring produce such as mushrooms, citrus, asparagus, strawberries, grapes and broccoli. As low permeability to O_2 compared to CO_2 is the characteristic of most films. The levels of atmosphere attained using traditional MAP are rarely sufficient to ensure longer shelf life and maintain quality produce during storage (Mahajan et al., 2008; Mangaraj et al., 2009; Sandhya, 2010). Thus, anaerobiosis and development of undesirable off-odours under low O_2 and elevated CO_2 atmospheres are common occurrences that severely modify volatiles profile of packaged produce (Oms-Oliu, Soliva-Fortuny, & Martín-Belloso, 2007; Rojas-Grau et al., 2009; Caleb et al., 2013a). Alternatively, the use of perforations in perforation-mediated modified atmosphere packaging (PM-MAP) has been proposed as a technique to overcome these limitations (Rodriguez-Aguilera & Oliveira, 2009; Oliveira, Sousa-Gallaghera, Mahajan & Teixeira, 2012a).

Perforations in MAP are used to achieve higher transmission rates of gases and water vapour through commonly used polymeric films (Del-valle et al., 2004; Gonzalez, Ferrer, Oria, & Salvador, 2008). The technique involves use of single, multiple perforations or tubes on polymeric films to allow for regulation of gas and water vapour exchange rates in packaged fresh produce (Riad, Brecht, & Chau, 2002; Montanez, Oliveira & Frias, 2005; Mahajan et al., 2008). Several authors have analyzed the impacts of perforations on gas and water vapour exchange rates as being beneficial in generating safe and desirable modified atmosphere within packages of fresh produce (Gonzalez et al., 2008; Pandey & Goswami, 2012).

3.2. Principles and functions of PM-MAP

Micro-/Macro perforations are developed to improve film permeability to O_2, CO_2 and water vapour above that of the original film alone (González-Buesa, Ferrer-Mairal, Oria, & Salvador, 2012; Mir & Beaudry, 2004), due to the fact that the exchange of gases through the film takes additional route of perforations (Lange, 2000; Pandey & Goswami, 2012). Use of perforations in PM-MAP fosters rapid and sufficient build-up of adequate CO_2 and O_2 levels to establish a safe EMAP (Gonzalez et al., 2008; Kartal, Aday, & Caner, 2012). Perforation-mediated MAP potentially reduces the risk of anaerobiosis and microbial growth associated with moisture condensation due to fluctuating temperatures (Fonseca et al., 2000; Lee & Renault, 1998; Silva et al., 1999a). The exchange of O_2 and CO_2 through perforations on the packaging film facilitates the achievement of the desired gas equilibrium within the package.

Perforation-mediated MAP is a useful technique to achieve safe modification of internal atmosphere of package for safe storage and quality retention of horticultural produce in comparison with conventional non-perforated MAP system (Riad et al., 2002; Montanez et al., 2005). High and medium respiratory produce such as cherries, strawberries blueberries, sweet corn, spinach and mushroom require relatively high concentration of CO_2 and low O_2, and the use of perforated packaging system provides an alternative means to equilibrate the in-package gas composition, in which a reduced O_2 and relatively higher CO_2 is achieved. In addition, besides improving gas and moisture transfer, perforating an airtight package serves other crucial functions in MAP. For instance, the use of perforations has been reported to shorten cooling time and prevent condensation of water vapour inside the package. Furthermore, perforation can be used to achieve safe and desired atmospheres inside package through the effects on altering film permeability as well as a means to attain pressure equilibrium inside the package (Oliveira et al., 1998; Fonseca et al., 2000).

4. Perforation methods for packaging films

The design process of PM-MAP is complex because each produce has its specific and often unique packaging requirements (Mahajan et al., 2007). As a result, a number of variables need to be optimized simultaneously so as to meet the target MAP for specific produce (Rodriguez-Aguilera & Oliveira, 2009). Designing process needs to consider the gaseous composition requirement (O_2

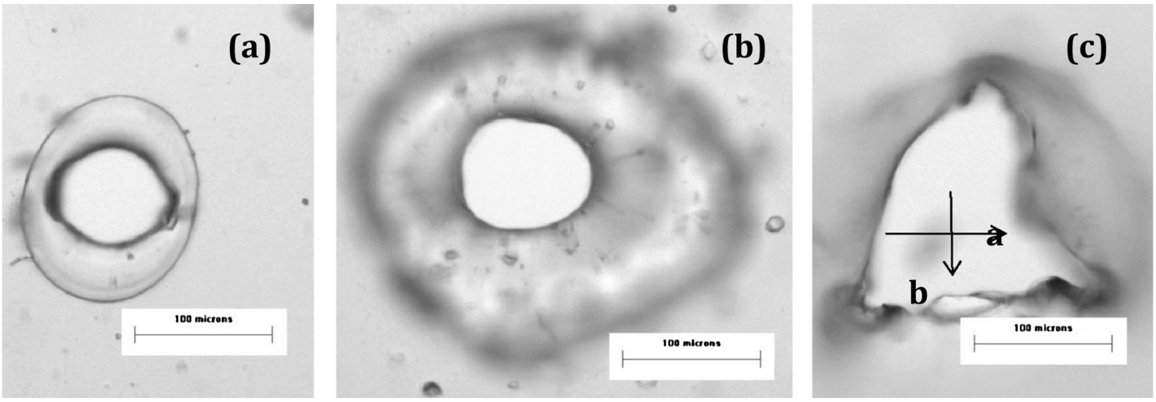

Fig. 1. Pictures of different perforations (a) laser micro-perforation-BOPP, (b) laser micro-perforation-PET and (c) mechanical perforation-PET. *a* is the horizontal diameter, *b* is the vertical diameter.
Adopted from Larsen and Liland (2013).

consumption and CO_2 production rates) of specific produce, the mass transfer coefficients for the gas exchange through the packaging material and the response of these MAP parameters to change in environmental factors such as storage temperature (Mahajan et al., 2007; Rodriguez-Aguilera & Oliveira, 2009). PM-MAP system design must take into account the number and dimensions of the perforations as the major factors controlling the exchange rate of relevant gases through the perforations (Kartel et al., 2012; Montanez et al., 2010). Effects of changes in external environment (temperature and atmospheric pressure) on the rate of mass transport through perforations are another critical factor that should be taken into consideration (Montanez et al., 2010). Therefore, optimal PM-MAP design is dependent on knowledge of these variables and their correlation with the mass transfer coefficients of packaging films (Fonseca, Oliveira, & Brecht, 2002; Montanez et al., 2010). Table 2 summaries the important factors to consider during PM-MAP design process.

Perforations vary in size from micro-perforations (50–200 μm diameter holes or tubes) to macro-perforations with holes or tubes greater than 200 μm in diameter (González-Buesa, Ferrer-Mairal, Oria & Salvador, 2012; Gonzalez et al., 2008; Lange, 2000). A number of techniques have been developed to produce such perforations in polymeric films, including the use of tube perforation, mechanical/semi-automated cold or hot needle puncturing and most recently, laser technology (Gonzalez et al., 2008; Gonzalez-Buesa et al., 2012). Therefore, the microstructures of the perforation depend on the perforation method used and the type of polymeric film perforated as shown in Fig. 1. Microstructural characteristics such as size, shape, spacing and number of micro-perforations are important when producing plastic films for food packaging applications (Allan-Wojtas et al., 2008), due to the effects of these factors on gas permeation and establishment of precise O_2 and CO_2 atmospheres in MAP (Allan-Wojtas et al., 2008; Larsen & Liland, 2013).

4.1. Tube perforation

Earlier studies on PM-MAP have reported the use of tubes (Emond, Castaigne, Toupin, & Desilets, 1991; Fonseca et al., 2000; Lee & Renault, 1998; Ratti, Rabie, & Raghavan, 1998; Silva, 1995). Montanez et al. (2005), investigated the design of PM-MAP using one or more tube perforation for shredded carrots via mathematical modeling and experimental validation. The authors reported that dimensions of the PVC tubes used for perforation and the amount of produce influenced the change in gas composition inside the package. Effect of different hydrodynamic conditions based on change in storage temperature (5, 10 and 15 °C) and PVC tubes dimensions (length from 2 to 6 mm; diameter 1.5–4.5 mm) on gas exchange rate in PM-MAP was reported by Montanez et al. (2010). Although, the application of tube perforation for MAP has been investigated for strawberries (Silva, 1995; Silva, Chau, Brecht & Sargent, 1999b), shredded carrots (Montanez et al., 2005), and mathematical model developed by Mahajan et al. (2008) and Montanez et al. (2010), there are limited reports on the application of tubes in MAP, probably due to practical difficulties of using tubes on packages.

4.2. Cold or hot needle perforation

This technique is also frequently described as pin-perforation, which involves manual or semi-automated mechanical perforation of polymeric film. It is a slow and time consuming method and usually produces large perforations ($\geq$1 mm in diameter) (Piergiovani, Limbo, Riva, & Fava, 2003). While hot needles melt the plastic to form the hole and redeposit the melt plastic as a large rim around the edges, cold needles punch rough holes in the plastic film, leaving the plastic material from the holes attached as flaps that can cover the holes (Allan-Wojtas et al., 2008). Mechanical perforation of packaging film has been applied extensively for the storage of several fresh produces. This include sweet corn (Riad et al., 2002), tomato (Li, Li, & Ban, 2010), capsicum (Pandey & Goswami, 2012), spinach, parsley and dill (Zenoozian, 2011), minimally processed pomegranate arils (Hussein et al., 2015), mandarin (Del-Valle, Hernández-Muñoza, Catalá, & Gavara, 2009), litchi (De Reuck, Sivakumar, & Korsten, 2009), strawberries (Kartal et al., 2012), and broccoli (Fernandez-León et al., 2013). Li et al. (2010) investigated transmission rate of O_2, CO_2 and water vapour of micro-perforated MAP films with thickness of 0.03 and 0.05 mm, perforation diameters of 0.5 and 2.0 mm under different storage temperatures of 0, 10 and 20 °C. The authors described the described the behaviour of tomato under the different packaging and storage conditions.

The success of mechanical needle perforation in MAP can be attributed to the flexibility, cost effectiveness and the fact that it does not require complex technical details. However, it is time consuming and difficult to achieve consistent perforation (Mir, 2009; Larsen & Liland, 2013). The irregular hole made with the needle may simulate the shape of holes made by different mechanical puncturing equipments (Larsen & Liland, 2013). Manufacturing of perforated films of right number and diameter of holes on the film on a consistent basis has been the most challenging process (Gorny, Brandenburg & Allen, 2003). Furthermore, it has been established that the flow rate through every single perforation is dependent on geometric features of the perforation inlet and exit (Disimilie, Fox, & Lee, 1998). Larsen and Liland (2013) indicated that mechanical perforations have irregular shapes, and therefore, it is usually difficulty to calculate the accurate area, in comparison to laser perforations. This suggests that during the model development and PM-MAP design process, the type of perforation method used should be considered in order to achieve a desirable gas transmission rate. Micro-electric discharge machining (micro-EDM) also known as sparks eroding is a relatively new technique used for micro-perforation of plastic films. With this method, plastic material is removed by melting and vaporization caused by a series of electrical discharges (sparks) provided by a generator to produce micro-perforations on film (Allan-Wojtas et al., 2008).

4.3. Laser perforation

Laser perforation systems consist of three important components which include a medium that generates the laser light, a power source that discharges energy in excited form to the laser medium to emit laser beams, and an optical cavity that compress the beam to stimulate the emission of laser radiation (Mir, 2009). Laser-drilled perforation uses heat energy to evaporate plastic film to produce small, clean holes that are sealed along the edges. Depending on the plastic used, evaporated material may be completely evaporated or some may redeposit on the surface of the film (Lazare & Tokarev, 2004; Allan-Wojtas et al., 2008). Perforation of plastic films is achieved by standard CO_2 laser systems operated well for speeds about 300′ per minute. Above this standard speed, the consistency of laser holes is significantly reduced and the holes might be partially perforated or not perforated (Mir, 2009). Technological improvements in power source from 20 to 2 kW, from split beam approach to beam compression and to the use of polygon mirror, which ensures the consistency of the beam strength (Dinauer & Gaebler, 2008; Mir, 2009). Although technological advancement has been gained in the development of efficient laser perforation systems for polymeric films, production cost will play a significant role in commercialization. Furthermore research into produce specific packaging solution is needed in order to fully benefit from this technology.

5. Mass transport analysis in perforation-mediated MAP

Mass transfer is an important physical phenomenon that influences the movement of gases and water vapour through MAP films. Mass transport of gases inside the package is driven by a dynamic process balanced by respiration of produce and gas permeation through the package (Mir & Beaudry, 2004; Mahajan et al., 2008). The flow of gases and water vapour through holes in perforation-mediated MAP is usually a combination of convection and diffusion (González-Buesa et al., 2012). In relatively impermeable films gas exchange of a package occurs almost entirely through the microperforations (González-Buesa et al., 2012). Exchange of gases between packaging film and surrounding atmosphere is driven by the partial pressure gradient across MAP film (Mullan & McDowell, 2011). In perforation-mediated MAP, most of the gas exchange occurs through the perforations, while in packages with a low number of perforations the gas flux is usually by a combination of transmission through the polymer material and transmission through the perforations (Beaudry, 2008). This phenomenon is dependent on the number, length and position of perforations, area covered, and film thickness (Oliveira et al., 1998). For example, two perforations of same size may not give a double effect of a single perforation due to poor position or disproportionate surface area and could induce a draft inside the package, resulting in poor gas distribution which is detrimental to product quality (Emond and Chau, 1990). Similarly, film thickness could influence the effective gas exchange through the film, by slowing down the transmission/permeation rate (Fonseca et al., 2000). However, Techavises and Hikida (2008) investigated the effect of macro-perforation from 2 to 15 mm on LDPE films of 0.012 and 0.025 mm thickness. The authors established that film thickness had no significant effect on effective gas exchange.

The rate at which O_2 is consumed and CO_2 is produced by respiring fresh produce inside MAP depends on the concentrations of O_2 and CO_2 at a given temperature (Mangaraj, Goswami, Giri, & Tripathi, 2012). In this regard, barrier properties of packaging films in relation to the molecules of O_2, CO_2 and water vapour, plays a significant role in MAP of fresh whole and minimally processed produce. Relevant gases (CO_2, O_2) permeate in and outside the package across the film and/or through perforations thereby influencing changes in quality and shelf life of produce. Mass transfer by diffusion mechanism starts with the sorption of molecules into barrier surface by diffusional molecular exchange followed by desorption on the opposite surface (Hu, Topolkaraev, Hiltner, & Baer, 2001; Rodriguez-Aguilera & Oliveira, 2009).

Under non-perforated MAP system that uses conventional polymeric films the ratio of the permeability for CO_2 and O_2 (permselectivity, PCO_2/PO_2), commonly denoted as β for different polymeric films generally vary from 2 to 8 (Al-Ati & Hotchkiss, 2003; Beaudry, 2008; Gonzalez et al., 2008). Al-Ati and Hotchkiss (2003) described the influence of PCO_2/PO_2 film permselectivity in the headspace of packaged fresh-cut apples based on ordinary differential equations coupled with Michaelis–Menten parameters obtained from respiration rate of the produce. The authors suggested that effect of permselectivity can be estimated by calculating the equilibrium gas composition with different permeability coefficients. Bearing in mind that the respiration coefficient of the packaged product can fluctuate between 0.7 and 1.3, if there is no temperature abuse, a relatively high concentration of CO_2 is reached in containers with non-perforated films (González-Buesa, 2012). However, in perforation-mediated MAP systems, the scenario is quite different such that CO_2 diffuses 0.77 faster than O_2, thus resulting in more or less equal generation of gradient of gases with a β value close to 1 (Brody, 2008; Mahajan et al., 2008; Ozdemir, Monnet, & Gouble, 2005). That means, in perforation-mediated MAP, the atmospheres with elevated CO_2 concentrations can be achieved without the quantity of O_2 in the package dropping rapidly towards detrimental anaerobic conditions.

Gas permeability of micro-perforated polymeric films can be measured by either static or dynamic system or method. However, most experimental systems for measuring the permeability of perforated or micro-perforated plastics are static because in these cases the flow through the perforation only follows gas diffusion mechanisms (Ghosh & Anantheswaran, 2001; González-Buesa et al., 2009, 2012). In addition, the small differences in pressure on both sides of the perforation may result in serious errors in the measurements using dynamic system (González-Buesa et al., 2012). The setup of static gas permeability measurement consists of a cell, divided by the test film into two compartments, the bottom part with an inlet and outlet tubes for gas flushing and the top open to the atmosphere (Ghosh & Anantheswaran, 2001). One of the static methods reported for measuring gas permeability is a flow-through method which had adequate control of the pressure at both sides of the micro-perforation (Ghosh & Anantheswaran, 2001), unlike dynamic methods which are of doubtful due gas convection that takes place when the pressures between the two cells are even just slightly unbalanced (González-Buesa et al., 2012).

Conventional polymeric films used in fruit and vegetable packaging have lower water vapour transmission rates relative to the transpiration rates of fresh products. High humidity conditions prevail in the packages, causing moisture condensation, microbial growth and decay of the product. Additionally, excess moisture in packages can have detrimental effect on products such as caking of powdered/flour products and softening of fresh produce. In contrast, excessive moisture loss from packaged produce may result in desiccation (Brody, Bugusu, Han, Sand, & McHugh, 2008). The exchange of water vapour through MAP film is crucial due to its potential role in regulating in-package humidity, which in turn influences produce physiological responses and quality (Dirim, Ozden, Bayındırlı, & Esin, 2004; Techavises & Hikida, 2007).

Permeability properties of packaging film with high WVTR such as hydrophilic polymers influence the effect of perforations to water vapour permeability (Mistriotis et al., 2011). As a result, excess moisture due to transpiration diffuses across the film surface while O_2 and CO_2 permeate through perforations (Briassoulis, Giannoulis & Mistriotis, 2012; Mistriotis et al., 2011; Mistriotis & Briassoulis, 2012). Perforation-mediated modified atmosphere packaging system takes control of both respiration and transpiration process through adjustment of gases and water vapour to generate desirable EMAP for a specific horticultural produce (Briassoulis et al., 2012). Design of the EMAP system to regulate water vapour condensation should not only consider the respiration but also the transpiration rate of packaged produce (Caleb, Mahajan, Al-Said, & Opara, 2013b; Xanthopoulos, Koronaki, & Boudouvis, 2012). Regulation of these two processes is the key to efficient EMAP of fresh produce (Mistriotis & Briassoulis, 2012; Song, Vorsa, & Yam, 2002).

6. Mathematical modelling of gases and water vapour in PM-MAP

Mathematical modelling of gas and water vapour movement through perforated films has been successfully used to design package and predict film properties (Fishman, Rodov, & Ben-Yehoshua, 1996; Ghosh & Anantheswaran, 2001; González-Buesa et al., 2009). Design of perforation mediated-MAP involves the application of mathematical models capable of predicting of gas and water vapour permeability through the film as a function perforation combined with the adequate understanding of the physiology response (transpiration and respiration rate) of the produce (Fishman et al., 1996). Mathematical models simulating various conditions of MAP are useful tools in design and validation of correct MAP (Montanez et al., 2005; Mahajan et al., 2007; Pandey & Goswami, 2012). Modelling allows pre-determination of key MAP determinant factors such as exchange rates of gases, water vapour and changes of in-package gas composition prior to MAP design (Kader & Watkins, 2000). Modelling of produce respiration and exchange of gas and water vapour or mass transfer through film and perforations is based on different physical laws. Graham's law of effusion, Fick's law and Stephan–Maxwell law of diffusion and/or a combination of more than one physical law have been used to predict permeation of gas and water vapour through non-perforated and perforated packaging systems (with micro-perforations) (Fishman et al., 1996; Gonzalez et al., 2008; Kader & Watkins, 2000). However, in some cases, the combination of diffusion and sorption laws (such as Henry's law for sorption) has proven not to be adequate in describing the mass transport process alone. In this case, Knudsen diffusion and effusion and/or hydrodynamic flow laws (such as Poiseuille's) have been applied to describe permeation of gas through perforated films (Del-valle et al., 2004; Gonzalez-Buesa, Ferrer-Mairal, Oria, & Salvador, 2009; Zanderighi, 2001).

Various mathematical models have been developed to describe gas exchange of perforation-mediated packaging system and prediction of O_2 and CO_2 mass transport coefficients, some of which are summarised in Table 3. Gas exchange through micro-perforated films takes either of the two major assumptions: (i) some models are developed based on perforations as the major route of gas transport with the final gas transfer rate being the additive term of permeation through perforation and diffusion across the film (Mir & Beaudry, 2004; Montanez et al., 2010); or, (ii) other models takes into account the transfer of gas through perforations, while assuming the film as impermeable (Del-Valle et al., 2009; Montanez et al., 2010). In cases where modelling of mass transport of gas through micro-perforated packaged produce is assumed to take place through multi-component including the commodity, headspace, perforations and/or permeable film, the Maxwell–Stefan equation has been used to determine diffusive flux of gases. This model was reported to be more appropriate for describing relationships between the fluxes and concentration gradients of gases in multicomponent systems (Chung, Papadakis, & Yam, 2003; Gonzalez-Buesa et al., 2012; Rennie & Tavoularis, 2009).

Most of the models for predicting gas exchange rates depend merely on the product RR and film permeability (also known as a steady-state or constant RR condition), normally simulated at a single temperature and very often at low RH (Kader & Watkins, 2000). Perhaps, possible large experimental errors, time consuming experiments for determination of RR for MAP and the complexity nature of the process are main limitations of many predictive models (Fonseca et al., 2002). However, during MAP design, the dynamism caused by temperature fluctuation during storage and distribution coupled with changing humidity conditions and consequent responses of film permeability to these changes need to be considered. The need for considering such dynamic processes in the modelling becomes crucial to avoid the risk of exposing the product to undesirable gas and humidity composition atmosphere (Kader & Watkins, 2000; Mahajan et al., 2007). The influence of storage temperature on gas transmission rate is different for continuous and perforated packaging films (Lange, 2000; Zanderighi, 2001; Larsen & Liland, 2013). Larsen and Liland (2013) reported that change in storage temperature from 5 °C to 23 °C for the average single perforations of oriented

Table 3
Summary of selected models for predicting exchange of gases and water vapour (WV) through perforated films.

Basis of the model	Mathematical equation	Number(s) of perforation (n)[a]	Film thickness (l)	Reference
Stephan–Maxwell's law (modified)	$-\frac{P}{RT}\left(\frac{Y_{i,k+1}-Y_{i,k}}{\Delta x}\right)=\varphi_{pi}\sum_{\substack{j=1\\ j\neq i}}^{n}\left(\frac{Y_{j,k}+Y_{j,k+1}}{2D_{ij}}\right)$	0, 6, 992	30 μm	Lee, Kang, and Renault (2000)
Fick's law	$J=-D(c_W)\frac{\partial c_W}{\partial x}$		28 μm	Del Nobile et al. (2007)
Stephan–Maxwell's law	$-\frac{P\partial C_1}{RT\partial l}=\varphi_{pi}\sum_{\substack{j=1\\ j\neq i}}^{n}\frac{\varphi_{pi}C_j-\varphi_p Y_i}{D_{ji}}$	1–5	$0.00284\leq n\leq 0.102$ cm	Paul and Clarke(2002)
Fick's law (modified)	$M_1=\frac{D_1A\Delta c}{l_1+\varepsilon}$			Chung et al. (2003)
Knudsen's law	$J_{k,A}=D_{k,A}\frac{\partial c_A}{\partial X}$	3–6	0.2 mm	Del-valle et al. (2004)
Fick's law	$WTR_z=-D\left[\frac{M_WAP_T}{RTpAlm}\right](pW_1-pW_2)$	1, 3, 6, 12, 18 and 24 (holes per 38.5 cm^2)	0.2, 0.5, 1.75 mm	Dirim et al. (2004)
Fick's law	$\frac{dO_2}{dt}=AkO_2\left(pO_2^{in}-pO_2^{out}\right)$	0.13 m^2 Diffusion area	35 μm	Ozdemir et al. (2005)
Fick's law	$\frac{dV(t)}{dt}=n_pD_i\left(P_i^{out}-P_i^{in}\right)$	1 hole	0.012, 0.025 mm	Techavises and Hikida (2008)
Fick's law	$J_{fi}=-\frac{P}{RT}\frac{Q_iA\left(P_i^{in}-P_i^{out}\right)}{L}$	0–14	40 μm	Gonzalez-Buesa et al. (2009)
Fick's law	$J_{fi}=\frac{A_fP_{fi}(C_{i,out}-C_{i,in})}{L_f}$	1 hole	45 μm	Gonzalez et al. (2008); Pandey and Gwasomi (2012)

[a] (n) and (l) refer to the number(s) of perforation and thinkness of film investigated.

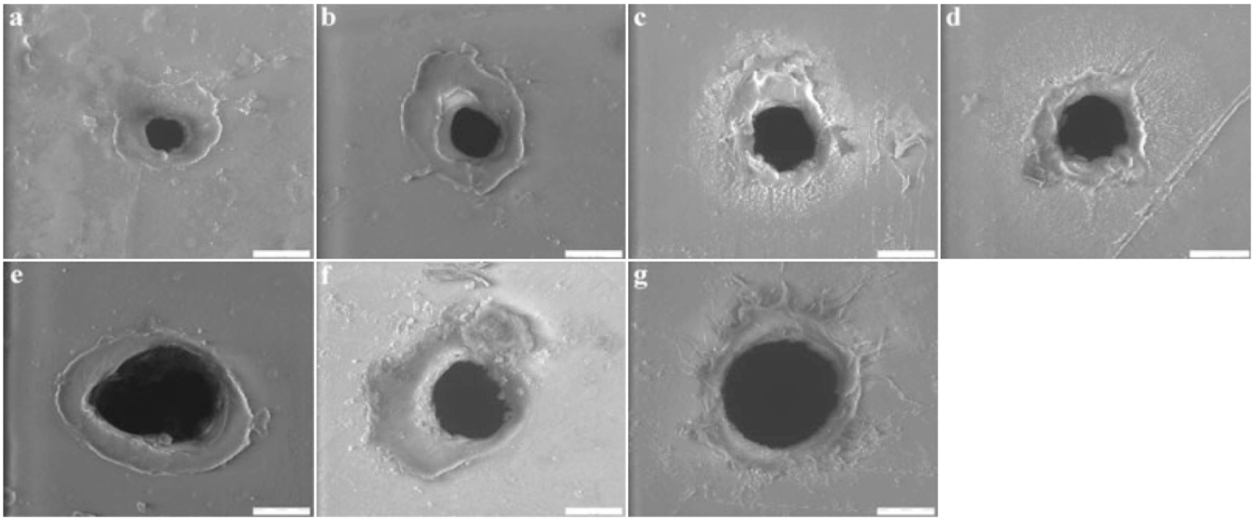

Fig. 2. Digital images of surfaces of mechanically produced perforations on polyester film with the smallest (a) through to largest (g) measured area (μm^2). Bar = 50 μm captured using low-vacuum scanning electron microscopy (LV-SEM). Images demonstrate the variability in perforation size. The O_2 and CO_2 transmission rates determined for these samples varied significantly due to differences in circularity values for the perforations of similar size.
Adopted from Allan-Wojtas et al. (2008).

polypropylene/polyethylene (OPP/PE) top web had no significant effect on the O_2TR and CO_2TR while it increased by a factor of 2.4 for the non-perforated package.

Furthermore, most of the developed models traditionally assume the uniform production of micro-perforations that are round, within the required size range, and unobstructed (Allan-Wojtas et al., 2008). However, in many practical cases, there is always variability in the shape, size and uniformity of the micro-perforations drilled on the film as shown in Fig. 2. As the result, measured permeability of micro-perforated films fails to agree with predicted values which lead to subsequent unpredicted and possible undesirable gas concentrations in MAP packages. Allan-Wojtas et al. (2008) reported that microstructural characteristics such as shape and size of micro-perforations using different microscopy techniques affected the O_2 and CO_2 transmission rate of polyethylene and polyester films. Accordingly, a linear increase of both O_2 and CO_2 transmission rates with the area of the holes for micro-perforations in the range of 30–100 μm, for diffusion under calm conditions was observed. In addition, perforations of same dimension made by different methods may vary in rates of transmission of gases. Larsen and Liland (2013) reported that perforations made by the acupuncture needle of calculated area (mean value) of 6500 μm^2 in the Amcor P-plus PET/PE-film had the highest O_2TR and CO_2TR, almost threefold the values for the laser perforations in the PET/PE-film and BOPP-film. Based on that, it is always important to take into consideration the named micro-structural characteristics as important factors that may affect the modelling process and hence, leading to discrepancy between experimental and predicted values.

7. Determination of crop specific PM-MAP

One of the most challenging aspects of PM-MAP design is getting the right number and dimension of holes per area of the film to match the required gas composition of packaged produce. The atmosphere inside the package is determined by the total surface area of the holes on the package surface (Gorny, Brandenburg & Allen, 2003). It is well known that in-package gas composition is influenced by the respiration rate of the product and the gas permeability of the packaging film (Mahajan et al., 2008). Therefore, when designing the perforation-mediated MAP, the produce to be packaged defines the rate of O_2 consumption and CO_2 generation of packaging film. Therefore, it is pertinent to say that the produce determines the recommended concentrations of O_2 and CO_2 gases to be achieved within MAP (Gorny, Brandenburg & Allen, 2003).

In principle, if fruit respiration does not correlate with the permeability properties of the packaging film, anaerobic respiration and ethanol accumulation inside the fresh produce will set in due to build-up of concentrations of CO_2 (Caleb, Opara, & Witthuhn, 2012). This results in the development of off-flavours and decay of packaged produce (Caleb et al., 2012; Waghmare et al., 2013). Once the RR of the produce is known, the optimal packaging can be designed by adjusting amount of product, size of packaging material, and perforation density (Caleb et al., 2012). Studies on predictive modelling of the RR of fresh whole fruit or minimally processed produce could be used to determine the adequate number of perforations required to achieve a particular gas composition for safe storage.

A number of studies have been conducted using mathematical modelling to describe the effect of various parameters such as time and temperature on respiration rate of different types of fresh produce such as fresh-cut (Waghmare et al., 2013), pomegranate fruit and arils (Caleb et al., 2012), sliced mushroom (Iqbal, Rodrigues, Mahajan, & Kerry, 2009), and shredded carrots (Iqbal et al., 2005). Overall, results from these models had been useful for selecting suitable packaging film, thus minimizing the number of experiments required for designing optimal MAP for selected fresh-cut produce (Waghmare et al., 2013). Similar approach could be a useful means to determine a crop specific perforation in determining the optimum number of micro-perforations to maintain quality and extend shelf life of each specific fresh produce.

Current MAP design takes into consideration the produce respiration rate as the only important parameter for deciding target oxygen (O_2) properties required to achieve equilibrium suitable for the selected product (Caleb et al., 2013a). However, it is also important to take into consideration the in-package level of humidity for fresh produce, in order to avoid moisture condensation and potential mould and bacterial development in MAP systems (Song et al., 2002). Predicting the RR and transpiration rate (TR) of fresh produce at a particular storage temperature and gas composition is the first approach towards establishing the required film permeability for PM-MAP of specific produce (Caleb et al., 2013a; Waghmare et al., 2013). Caleb et al. (2013a) developed a mathematical model to relate the TR to temperature and RH. Based on the fact that the in-package RH is influenced by TR of the produce as well as by the water vapour permeability of the packaging film, TR model developed for arils was used for estimating the target WVTR required to maintain optimal RH inside the package.

The established relationship between WVTR of the film, storage temperature and the desired RH with the package was essential to estimate the packaging needs of pomegranate arils, and packaging materials of suitable permeability was recommended on that basis. Similarly, Aindongo, Caleb, Mahajan, Manley, and Opara (2014) investigated the optimal RH and storage temperature critical in designing the MAP system of pomegranate arils and aril-sacs based on TR model. The results obtained from the prediction using TR model follow the same trend as those reported by Caleb et al. (2013b) for pomegranate (cv. Acco). Mahajan et al. (2008) established the relationship between different perforation dimensions (diameter: 9, 13 and 17 mm; length: 10, 20 and 30 mm), storage temperatures (4, 10 and 16 °C) and WVTR. The authors went further to develop a mathematical model to describe the changes in WVTR as a function of perforation diameter, length, porosity and storage temperature. Following a successfully model validation at 7 °C, an experiment with mushrooms was conducted and revealed that the perforation-mediated modified atmosphere packaging could be used for fresh produce provided that the condensation is minimised by using a moisture absorber. Therefore, in order to determine a tailor-made packaging system, the design of micro-perforated polymeric films for MAP should involve predicting the permeability necessary for the gases exchanged and how to achieve this depending on factors such as the storage temperature, the type of polymeric material used, the number and size of the holes and the composition of the packaging atmosphere (González-Buesa et al., 2012).

8. Quality of fresh and minimally processed produce under PM-MAP in comparison to standard MAP

Extensive review of literature summarized in Table 4 shows that PM-MAP has been applied more extensively on whole fresh fruit and vegetables and less to fresh minimally processed produce. This includes fresh produce such as strawberries (Sanz, Perez, Olıas, & Olıas, 1999; Sanz, Olias & Perez, 2000; Almenar et al., 2007), broccoli (Fernandez-León et al., 2013), loquat fruit (Amoros et al., 2007), sweet corn (Riad et al., 2002), sliced mushrooms (Simón, González-Fandos, & Tobar, 2005; Oliveira et al., 2012a), mandarin (Del-Valle et al., 2009) and many other high and medium respiring produce. However, researchers have recommended the need for systematic approach in order to obtain a successful application of PM-MAP (Mahajan et al., 2007; Montanez et al., 2010; Oliveira et al., 1998). Scientific research and validation of PM-MAP technique is therefore needed for each specific produce in order to develop commercially applicable solutions for industry.

Almenar et al. (2007) evaluated the effects of micro-perforations on generation of EMAP suitable for safe storage of wild strawberries under 10 °C. In comparison to non-perforated packages, micro-perforated films with one and three perforations provided adequate CO_2 and O_2 equilibrium concentrations in view of the evolution of chemical and physical quality parameters. The authors reported that the use of polyethylene terephthalate (PET)/polypropylene film with one and three perforations (average diameter of 100 μm) heat-sealed on plastic cups (125 mL capacity) retained the quality of strawberries through the generation of adequate equilibrium concentrations of gases (4–13 kPa CO_2 and 5–18 kPa O_2). The authors concluded that 6 days shelf-life was achieved for strawberries packaged in MAP with three perforations while maintaining berry quality with little or no incidence of fungal decay and off flavours. Strawberries in non-perforated packages showed development of off-flavour towards end 6 days of shelf-life storage was which related to the accumulation of acetaldehyde, ethyl acetate and ethanol caused by anaerobic respiration.

Similarly, De Reuck, Sivakumar, and Korsten (2010) reported that quality of litchi (cv. McLean's Red) was maintained for up to 21 days less than 2 °C packaged in perforated MAP with 10 perforations (0.6 mm diameter). However, the authors did not describe the gas exchange area that was perforated. The EMAP of 17 kPa O_2 and ~5 kPa CO_2 was attained within 6 days of storage

Table 4
Selected studies on the application of perforation-mediated MAP for fresh and fresh cut produce.

Produce	Type of PM-MAP		Gas composition (CO_2/O_2) (kPa)	Storage temp. (°C)	Shelf life (days)	Reference
	No. of holes/tubes	Perforated area (A)/diameter (D)				
Strawberries	2 or 4 holes	1.57 mm^2 or 3.14 mm^2	18.7/5 or 13.3/7.6	20	4	Sanz et al. (1999)
Mango fruit		75 × 75 cm^2 perforated area	~5/~15	12	21	Pesis et al. (2000)
Sweet corn		0.001% of 0.75 × 0.75 m^2	5CO_2	2	14	Rodov et al (2000)
Charentais melons		0.00025% of 0.56 m^2 size	13–14, CO_2, O_2	7	12	Rodov et al. (2002)
Sweet corn		4 mm D	15, 20 or 25, CO_2	1	10	Riad et al. (2002)
Strawberries	3 tubes	1.57, 3.14, 4.71mm^2	7.2–8.8/13.6–14.9	2	10	Sanz, Olias, and Perez (2002)
Sweet cherry		35 μm perforation D	3–4, CO_2	4	8	Alique, Martínez, and Alonso (2003)
Citrus fruit		0.002% perforated area)	2–3/17–18	6	35	Porat, Weiss, Sandman, & Shachnai (2009)
Sliced mushroom		0.102 m^2 perforated area	2.5/10–20	4	13	Simón et al. (2005)
Bananas	4 and 10 cm DC	50.29 cm^2 diffusion area	3.5/3	15	42	Stewart, Raghavan, Golden, and Gariepy (2005)
Litchi cv. *Mauritius*		0.00939% of 720 cm^2	6/17.0	2	34	Sivakumar and Korsten (2006)
Wild strawberries	1 and 2 holes	0.0785 m^2 perforated area	10/10	10	6	Almenar et al. (2007)
Loquat fruit		(20 × 30) cm^2 bag	16–18/2–4	2	14	Amoros et al. (2008)
Litchi cv. McLean's Red	10 holes	0.6 mm D	~5/~17	2	21	De Reuck et al. (2009)
Mandarin		~150 μm D	1.2/19.8	3	21	Del-Valle et al. (2009)
Fresh cut apple		2–100 μm D in 196 cm^2	7/14	5	21	Cliff, Toivonen, Forney, Liu, and Lu, (2010)
Mango	80–100 holes	~50–70 μm D	17/9	12	30	Boonruang et al. (2011)
Fresh sliced mushroom	2 holes	0.33 mm D	11.5/3.6	10	3	Oliveira et al. (2012a)
Broccoli		625 cm^2 A	5/10	5	12	Fernandez-León et al. (2013)
Strawberries	7 and 9 holes	90 μm D	15/5	4	>14	Kartal et al. (2012)
Cherry tomatoes	5 holes	200 μm D	4.0 ± 0.1 CO_2	20	60	Briassoulis et al. (2012)
Peaches	100 holes	200 μm D	3.3 ± 0.01 CO_2	20	12	Briassoulis et al. (2012)
Pomegranate arils	0, 3, 6 and 9	160.1 cm^2	0.1–34/1.3–19.2	5	15	Hussein et al. (2015)

DC, diffusion channels.

and successfully maintained quality attributes of Litchi including acceptable pericarp colour, total soluble solids (TSS), titratable acidity (TA) and TSS to TA ratio thereby preventing the loss of taste and flavour. However, after storage duration, litchi fruits of both cultivars packaged in non-perforated punnets had poor quality indicated by higher browning index due to accumulation of CO_2 to injurious levels within the punnets, higher decline in anthocyanin content and lower TSS/TA ratio. The observed higher oxidation enzymes activity in non-perforated punnets explains the loss of anthocyanin content and browning index noted in 'Mauritius', while the increase in acidity caused by fermentation and the observed higher CO_2 composition within the punnets were mentioned as primary cause for decrease in TSS/TA ratio.

The quality of fresh-cut 'Gala' apple slices stored in micro-perforated film was evaluated by Cliff, Toivonen, Forney, Liu, and Lu (2010). Micro-perforated film with a high O_2 and high CO_2 atmosphere was superior in terms of fruitiness, sweetness, firmness and higher fruitiness-by-mouth quality as compared to the standard solid film (non-perforated), with a low O_2 and high CO_2 atmosphere, for optimizing the quality of fresh-cut apple slices. The use of micro-perforated MAP (2–100 μm diameter perforations per package of $14 \times 14\,cm^2$) maintained both sensorial and physico-chemical quality attributes of apple slices such as volatile compounds, soluble solids concentration, titratable acidity, colour and relative juice loss for 21 days. Enhancement of quality attributes of fresh-cut 'Gala' apple slices was attributed to the established MAP composition (14 kPa O_2 and 7 kPa CO_2 partial pressures) and lower in-package of ethylene concentration.

However, besides the wide application of PM-MAP in the fresh horticultural food industry, there is a growing concern over the potential risk to permeation of moisture, volatile organic compounds and ingress of microorganisms through perforations, especially during wet or moist handling conditions (Chung et al., 2003; Del-valle et al., 2004; Dirim et al., 2004). The study conducted by Del-valle et al. (2004) reported a significant permeation of volatile organic compounds through a porous package which resulted in loss of odour and rapid deterioration of organoleptic properties of packaged produce. Furthermore, microbial contamination through perforations might be a hurdle towards the successful application of PM-MAP technology. This highlights the need for more research to evaluate the extent and severity of microbial safety of this postharvest technology. For this reason, it is recommended to use numerous micro-perforations ($<55\,\mu$m in diameter) to achieve desirable gas composition within MAP rather than using a few large perforation, which may cause transmission of contamination (Piergiovani et al., 2003).

Successful use of MAP to maintain quality and extend shelf-life of fresh produce must be accompanied by appropriate storage temperature, use of good quality of produce with minimal physiological damage and the application of appropriate treatments to reduce microbial spoilage (Krasnova et al., 2012). Various measures can be taken to reduce deterioration of fresh produce, including good agricultural and processing practices (such as harvesting produce at optimum maturity stage and minimising mechanical injuries), proper sanitation procedures, adherence to HACCP principles as well as the application of the optimal postharvest treatment (Artés, Gómez, Aguayo, Escalona, & Artés-Hernandez, 2009; Mahajan et al., 2014; Weerakkody, Jobling, Infante, & Rogers, 2010). This would help to minimize quality deterioration and the risk of microbial contamination in perforated modified atmosphere packages (Boonruang, Chonhenchob, & Singh, 2011; Oliveira, Sousa-Gallaghera, Mahajan & Teixeira, 2012b).

9. Conclusions and future prospects

Comprehensive review of literature indicated that the application of MAP and PM-MAP requires an integrated systemic approach. Based on specificity of packaging requirement for each produce, the need for better understanding of the critical factors influencing PM-MAP design was emphasised. These include adequate understanding of each produce specific requirements, the permselectivity properties of the packaging material and the storage conditions. Overall, the review showed that PM-MAP offer many benefits over conventional MAP through the ability to prevent anaerobiosis and establish desirable in-package gas composition for safe storage and quality retention of horticultural produce with medium to high respiration rates. Similarly, factors affecting the performance of PM-MAP system such as produce RR, film permeability and changes in external environment conditions (temperature and RH) were identified as important parameters to consider in the design process. Often the permeability data available are registered at ambient temperature (23 °C) and not at the desired optimum storage temperature for the produce. Hence it is necessary to take into consideration the permeability behaviour of packaging materials under produce storage temperature.

Despite the fact that PM-MAP has been proven as a potential postharvest tool to preserve quality and extend shelf life of various horticultural produce, there are still concerns to be addressed in order to gain consumer confidence. This includes produce microbiological safety, quality of packaged fresh produce during postharvest handling, the risk of permeation of moisture in product, and loss of volatile organic compounds (flavour). Therefore, future prospects must focus on investigating the effect of perforation on flavour life and microbiological quality and safety of MA-packaged fresh or minimally processed produce. Various mathematical models summarized in this review have been shown to be applicable in the design of PM-MAP. Important parameters such as multiple perforations, film thickness, and storage conditions that are amendable were identified. As new nano-composite- and bio-based films are introduced into the food packaging industry, further research into the interaction between fresh produce and packaging is required.

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