18 Packaging of Horticultural Products

18.1 INTRODUCTION

Fresh fruits and vegetables are essential components of the human diet as they contain a number of nutritionally important compounds such as vitamins and pigments that cannot be synthesized by the human body. A fruit or vegetable is a living, respiring and edible tissue that has been detached from the parent plant. Fruits and vegetables are perishable products with active metabolism during the postharvest period. In simple terms, the shelf life of fruits and vegetables can be extended by retarding the physiological, pathological and physical deteriorative processes (generally referred to as postharvest handling) or by inactivating the physiological processes (generally referred to as food preservation). Packaging has an important role to play in both the handling and preservation approaches to maximizing the shelf life; this chapter will primarily focus on the former since the packaging requirements of the preservation processes are not unique to horticultural products.

Difficulties arise when attempts are made to draw a clear line between fruits and vegetables. Fruits and vegetables cannot be clearly delineated botanically or morphologically as they encompass numerous organs in vegetative or reproductive stages and belong to a large number of botanical families. Fruits tend to be restricted to reproductive organs arising from the development of floral tissues, with or without fertilization, while vegetables consist simply of edible plant tissues. Thus, some fruits are included as vegetables and *vice versa*. Table 18.1 classifies horticultural produce according to the plant organ used, based mainly on the form in which the product is handled such as root, tuber, stem or leaf.

18.2 POSTHARVEST PHYSIOLOGY

Growth, maturation and senescence are the three important phases through which fruits and vegetables pass, the first two terms often being referred to as *fruit development*. *Ripening* (a term reserved for fruit) generally begins during the later stages of maturation and is considered the beginning of *senescence*, a term defined as the period when anabolic or synthetic biochemical processes give way to catabolic or degradative processes leading to aging and final death of the tissue.

18.2.1 RESPIRATION

Respiration involves the oxidation of energy-rich organic substrates normally present in cells such as starch, sugars and organic acids, to simpler molecules (CO_2 and H_2O) with the concurrent production of energy (ATP and heat) and other molecules which can be used by the cell for synthetic reactions. The principal carrier of free energy is ATP. The greatest yield of energy is obtained when the process takes place in the presence of molecular O_2. Respiration is then said to be aerobic. If hexose sugar is used as the substrate, then the overall equation can be written as follows:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy} \quad (18.1)$$

TABLE 18.1
Classification of Horticultural Produce according to the Plant Organ Used

Class	Commodities (Examples)
Root vegetables	Carrot, garlic, horseradish, onion, parsnip, radish, turnip
Tubers	Potato, yam, Jerusalem artichoke
Leaf and stem vegetables	Brussels sprouts, cabbage, celery, chicory, Chinese cabbage, cress, green onion, kale, lettuce, spinach
Flower vegetables	Artichoke, broccoli, cauliflower
Immature fruit vegetables	Bean, cucumber, gherkin, okra, pea, pepper, squash, sweet corn
Mature fruit vegetables	Melon, tomato
Reproductive organs	Most fruits

This transformation actually takes place in a large number of individual stages with the participation of many different enzyme systems. The water produced remains within the tissue but the CO_2 escapes and accounts for part of the weight loss of harvested fruits and vegetables, typically in the range of 3%–5%. When 1 mol of hexose sugar is oxidized, 36 mol of ATP (each possessing 32 kJ of useful energy) are formed. This represents about 40% of the total free energy change, the remainder being dissipated as heat. Rapid removal of this heat is usually desirable and it is important that the packaging assists, rather than impedes, this process.

The rate of respiration is often a good guide to the storage life of horticultural products: the higher the rate, the shorter the life; the lower the rate, the longer the life. Table 18.2 classifies vegetables according to their respiration intensities.

It is possible to evaluate the nature of the respiratory process from measurements of CO_2 and O_2. The ratio of the volume of CO_2 released to the volume of O_2 absorbed in respiration is termed the *respiratory quotient* (*RQ*). Values of *RQ* range from 0.7 to 1.3 for aerobic respiration, depending on the substrate being oxidized: $RQ = 1$ for carbohydrates, $RQ < 1$ for lipids and $RQ > 1$ for organic acids (Kader and Saltveit, 2003a).

Anaerobic respiration (sometimes called *fermentation*) involves the incomplete oxidation of compounds in the absence of O_2 and results in the accumulation of ethanol and CO_2:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 + \text{energy} \tag{18.2}$$

Much lower amounts of energy (2 mol of ATP) and CO_2 are produced from 1 mol of hexose sugar than that produced under aerobic conditions. In addition, compared to aerobic respiration, very little

TABLE 18.2
Classification of Vegetables according to Respiration Intensity

Class	Respiration Intensity at 10°C; mg CO_2 kg^{-1} h^{-1}	Commodities
Very low	Below 10	Onion
Low	10–20	Cabbage, cucumber, melon, tomato, turnip
Moderate	20–40	Carrot, celery, gherkin, leek, pepper, rhubarb
High	40–70	Asparagus (blanched), eggplant, fennel, lettuce, radish
Very high	70–100	Bean, Brussels sprouts, mushroom, savoy cabbage, spinach
Extremely high	Above 100	Broccoli, pea, sweet corn

energy (~5%) is produced for a given amount of carbohydrate oxidation in anaerobic respiration. The O_2 concentration at which a shift from aerobic to anaerobic respiration occurs varies among tissues and is known as the extinction point (Kader and Saltveit, 2003a). Very high RQ values (>1.3) usually indicate anaerobic respiration.

18.2.1.1 Internal Factors Affecting Respiration

Variations in the rate of respiration occur during organ development; as fruits increase in size, the total amount of CO_2 emitted increases, although the respiration rate calculated on a per unit weight basis decreases continually. A majority of studies on gas exchange in plant tissues indicate that the skin represents the main significant barrier to diffusion. Clearly, the rate at which the three gases O_2, CO_2 and C_2H_4 diffuse through the tissue will have a significant effect on the rate of respiration.

Fruits may be divided into climacteric and nonclimacteric types. Climacteric fruits are those in which ripening is associated with a distinct increase in respiration and C_2H_4 production, with the respiration rate rising up to the climacteric peak and then declining. Such an increase can occur either while the fruit is attached to or separated from the plant. A further distinguishing feature is that treatment of climacteric fruits with C_2H_4 or propylene stimulates both respiration and autocatalytic C_2H_4 production. Low temperatures greatly reduce the magnitude of the climacteric. The climacteric generally coincides with changes associated with ripening such as color changes, softening, increased tissue permeability and the development of characteristic aromas. Typical climacteric fruits include apples, pears, peaches, nectarines, bananas, mangoes, plums, tomatoes and avocados.

In nonclimacteric fruits, ripening is protracted and the attainment of the ripe state is not associated with a marked increase in respiration or C_2H_4 production. Treatment of nonclimacteric fruits with C_2H_4 stimulates respiration only; there is no increase in autocatalytic C_2H_4 production. Citrus, strawberries and pineapples are examples of nonclimacteric fruits.

Generally, vegetables do not show a sudden increase in metabolic activity that parallels the onset of the climacteric in fruit, unless sprouting and regrowth is initiated.

18.2.1.2 External Factors Affecting Respiration

18.2.1.2.1 Temperature

Temperature is the most important environmental factor in the postharvest life of horticultural products because of its dramatic effect on the rates of biological reactions including respiration (Kader and Saltveit, 2003a). Typical Q_{10} (the ratio of the respiration rates for a 10°C interval) values for vegetables are 2.5–4.0 at 0°C–10°C, 2.0–2.5 at 10°C–20°C, 1.5–2.0 at 20°C–30°C and 1.0–1.5 at 30°C–40°C. Taking mean Q_{10} values, it can be calculated that the relative rate of respiration would increase from 1.0 at 0°C to 3.0 at 10°C, 7.5 at 20°C, 15.0 at 30°C and 22.5 at 40°C. These figures dramatically illustrate the need to reduce the temperature of fresh fruits and vegetables as soon as possible after harvesting in order to maximize the shelf life.

The rate of increase in respiration rates declines with an increase in temperature up to 40°C, with the Q_{10} becoming less than 1 as the tissue nears its thermal death point (about 50°C–55°C) when enzyme proteins are denatured and metabolism becomes disorderly (Kader and Saltveit, 2003a).

The storage life of some fruits and vegetables, primarily those of tropical or subtropical origin, can be limited by chilling injury, a disorder induced in whole plants or susceptible tissues by low (0°C–12°C) but nonfreezing temperatures. The extent of the chilling injury is influenced by the temperature, the duration of the exposure to a given temperature and the chilling sensitivity of the particular fruit or vegetable. The symptoms of chilling injury may not be evident while the produce is held at chill temperatures, only becoming apparent after transfer to a higher temperature. Chilling injury prevents some fruits from ripening and increases their susceptibility to fungal spoilage. Chilling injury is generally associated with necrosis of groups of cells situated either externally, leading to the formation of depressed areas, pitting and external discoloration or internally leading to internal browning.

TABLE 18.3
Classification of Fruits according to Their Maximum Ethylene Production Rate

Ethylene Production Rate μL kg^{-1} h^{-1} at 20°C	Fruits
Very low: 0.01–0.1	Cherry, citrus, grape, pomegranate, strawberry
Low: 0.1–1.0	Blueberry, kiwifruit, peppers, persimmon, pineapple, raspberry
Moderate: 1.0–10.0	Banana, fig, honeydew melons, mango, tomato
High: 10.0–100.0	Apple, apricot, avocado, plum, cantaloupe, nectarine, papaya, peach, pear
Very high: >100.0	Cherimoya, mamey apple, passion fruit, sapote

Source: Kader, A.A., *Food Technol.*, 34(3), 51, 1980.

18.2.1.2.2 Ethylene

Ethylene is a natural plant hormone and plays a central role in the initiation of ripening. It is physiologically active in trace amounts (<0.1 ppm). The capacity to produce C_2H_4 varies greatly among fruits as shown in Table 18.3, with those fruits exhibiting moderate-to-very-high production rates generally being classified as climacteric fruits. Vegetables also produce C_2H_4, although data are comparatively scarce. Some typical figures in μL kg^{-1} h^{-1} at 20°C range from 0.04 for whole carrot roots, 0.02 for potato slices, 0.6 for intact cabbage head, 1.1 for summer squash, 1.7 for cauliflower head, 2.3 for Brussels sprouts, to 3.3–27.0 for broccoli head. Some fruit–vegetables such as tomatoes and melons are climacteric, while other fruit–vegetables such as cucumbers are not. The production of C_2H_4 by edible floral parts such as cauliflower and broccoli may be quite high and comparable with that of tomatoes.

When climacteric fruits are exposed to C_2H_4 during their preclimacteric stage, the time to the start of the climacteric rise in respiration is reduced. The magnitude of the final respiratory rise is controlled by the fruit's endogenous C_2H_4 production and is not influenced by added C_2H_4. A reduction in C_2H_4 production and sensitivity associated with modified atmospheres can delay the onset of the climacteric and prolong the storage life of these fruits.

When nonclimacteric tissues are exposed to C_2H_4, a climacteric-like rise in respiration is induced, proportional to the C_2H_4 concentration. Respiration rates return to their pretreatment level when the C_2H_4 is removed. Nonclimacteric fruits and vegetables can benefit from reduced C_2H_4 sensitivity and a lower respiration rate attributed to modified atmospheres.

The potent effects of C_2H_4 on plant growth, development and senescence mean that this gas, which is commonly found in the environment, can greatly reduce the storage life of perishable commodities sensitive to it. Important effects of C_2H_4 in hastening the deterioration of perishable commodities include accelerated senescence and loss of green color in leafy vegetables and some immature fruits (e.g., cucumbers, squash), accelerated ripening of fruits during handling and storage, russet spotting on lettuce, formation of a bitter compound (isocoumarin) in carrots, sprouting of potatoes, abscission of leaves (e.g., in cauliflower and cabbage) and toughening (lignification) of asparagus.

In addition to C_2H_4, several other hydrocarbons such as propylene and acetylene mimic the effects of C_2H_4 on respiration rates of fruits and vegetables (Kader and Saltveit, 2003a). Ethylene production is reduced by low O_2, high CO_2, or both and the effects are additive.

In 1994, it was discovered that the cyclic olefin 1-methylcyclopropene (1-MCP) was a specific inhibitor of ethylene action. Since that time, it has been used during postharvest storage to maintain quality by delaying ripening of partially ripe fruit through its effects on respiration, suppression of C_2H_4 production, volatile production, chlorophyll degradation and other color changes, protein and membrane changes, softening, disorders and diseases, acidity and sugars (Blankenship and Dole, 2003; Huber, 2008). It is complexed with γ-cyclodextrin to form a stable powder and when the powder is dissolved in water, 1-MCP is easily released as a gas (effective concentrations range from 0.25 to 1 μL L^{-1}) (Watkins, 2006). Treatment with 1-MCP is often combined with modification of the atmosphere.

18.2.1.2.3 Oxygen and Carbon Dioxide Concentration

A simple consideration of Equation 18.1 would suggest that if the CO_2 in the atmosphere were augmented (or the O_2 decreased), the respiration rate would be decreased and the storage life would be extended. Such is the case and the application of this approach is considered further in Section 18.3. However, fresh fruits and vegetables vary greatly in their relative tolerance to low O_2 concentrations (see Table 18.4) and elevated CO_2 concentrations (see Table 18.5), and optimum concentrations must be determined for each if modification of the atmosphere is to be successful.

Reduction of the O_2 concentration to less than 10% provides a tool for controlling the respiration rate and slowing down senescence, although an adequate O_2 concentration must be available to maintain aerobic respiration. Vegetable crops usually require a minimum O_2 content of 1%–3% in

TABLE 18.4
Classification of Fruits and Vegetables according to Their Tolerance to Low O_2 Concentrations

Minimum O_2 Concentration Tolerated (%)	Commodities
0.5	Tree nuts, dried fruits and vegetables
1.0	Some cultivars of apples and pears, broccoli, mushroom, garlic, onion, most cut or sliced (minimally processed) fruits and vegetables
2.0	Most cultivars of apples and pears, kiwifruit, apricot, cherry, nectarine, peach, plum, strawberry, papaya, pineapple, olive, cantaloupe, sweet corn, green bean, celery, lettuce, cabbage, cauliflower, Brussels sprouts
3.0	Avocado, persimmon, tomato, pepper, cucumber, artichoke
5.0	Citrus fruits, green pea, asparagus, potato, sweet potato

Source: Kader, A.A. et al., *CRC Crit. Rev. Food Sci. Nutr.*, 28, 1, 1989.

TABLE 18.5
Classification of Fruits and Vegetables according to Their Tolerance to Elevated CO_2 Concentrations

Maximum CO_2 Concentration Tolerated (%)	Commodities
2	Apple (Golden Delicious), Asian pear, European pear, apricot, grape, olive, tomato, pepper (sweet), lettuce, endive, Chinese cabbage, celery, artichoke, sweet potato
5	Apple (most cultivars), peach, nectarine, plum, orange, avocado, banana, mango, papaya, kiwifruit, cranberry, pea, pepper (chili), eggplant, cauliflower, cabbage, Brussels sprouts, radish, carrot
10	Grapefruit, lemon, lime, persimmon, pineapple, cucumber, summer squash, snap bean, okra, asparagus, broccoli, parsley, leek, green onion, dry onion, garlic, potato
15	Strawberry, raspberry, blackberry, blueberry, cherry, fig, cantaloupe, sweet corn, mushroom, spinach, kale, Swiss chard

Source: Kader, A.A. et al., *CRC Crit. Rev. Food Sci. Nutr.*, 28, 1, 1989.

the storage atmosphere and, at O_2 contents below 2%, most vegetables react with a sudden increase in CO_2 production. Glycolysis results in the formation of acetaldehyde, CO_2 and finally ethanol. Both acetaldehyde and ethanol are toxic to plant cells.

Elevated CO_2 levels can inhibit, promote or have no effect on C_2H_4 production by fruits. However, CO_2 has been shown to be a competitive inhibitor of C_2H_4 action, delaying fruit ripening by displacing C_2H_4 from its receptor site. The respiration rate of most root- or bulb-type vegetables when stored under elevated CO_2 levels is stimulated and, at concentrations above 20%, a significant increase in anaerobic respiration occurs which can irreversibly damage plant tissue.

Low O_2 and/or high CO_2 can reduce the incidence and severity of certain physiological disorders such as those induced by C_2H_4 (scald of apples and pears) and chilling injury of some commodities (e.g., avocado, citrus fruits, chili pepper and okra). On the other hand, O_2 and CO_2 levels beyond those tolerated by the commodity can induce physiological disorders such as brown stain on lettuce, internal browning and surface pitting of pome fruits and blackheart of potato (Kader et al., 1989).

18.2.1.2.4 Stresses

Physical damage such as surface injuries, impact bruising and vibration bruising can stimulate respiration and C_2H_4 production rates, depending on the variety of fruit or vegetable and the severity of the damage. The extent of the increase in respiration rate is usually proportional to the severity of bruising. However, the commercial implications of the bruising (i.e., the fact that consumers prefer not to purchase bruised fruits and vegetable) are of far greater importance than its effect on the respiration rate.

Water stress resulting from loss of water to the surrounding atmosphere can stimulate the respiration rate, although once the water loss exceeds 5%, the respiration rate may be reduced, coinciding with noticeable wilting and shriveling of the tissue (see next section).

18.2.2 TRANSPIRATION

18.2.2.1 Introduction

All fruits and vegetables continue to lose water through transpiration after they are harvested, and this loss of water is one of the main processes that affect their commercial and physiological deterioration. If transpiration is not retarded, it induces wilting, shrinkage and loss of firmness, crispness and succulence, with concomitant deterioration in appearance, texture and flavor. Most fruits and vegetables lose their freshness when the water loss is 3%–10% of their initial weight. As well as loss of weight and freshness, transpiration induces water stress which has been shown to accelerate senescence of fruits and vegetables.

18.2.2.2 Factors Influencing Transpiration

Several factors such as the surface area to volume ratio, nature of the surface coating, RH, temperature, atmospheric pressure and extent of any mechanical damage influence the transpiration process in fruits and vegetables.

The surface area to volume ratio can range from 50 to 100 $cm^2\ mL^{-1}$ for individual edible leaves to 5–10 $cm^2\ mL^{-1}$ for small soft fruits such as currants, 2–5 $cm^2\ mL^{-1}$ for larger soft fruits such as strawberries, 0.5–1.5 $cm^2\ mL^{-1}$ for tubers, pome, stone and citrus fruits, bananas and onions, to 0.2–0.5 $cm^2\ mL^{-1}$ for densely packed cabbage (Burton, 1982). Other factors being equal, a leaf will lose water and weight much faster than a fruit, and a small fruit or root or tuber will lose weight faster than a larger one.

While O_2, CO_2 and C_2H_4 diffuse mainly through air-filled stomata, lenticels, floral ends and stem scars, water vapor preferentially diffuses through the liquid aqueous phase of the cuticle (Zagory and Kader, 1988). In addition, there can be significant water vapor loss from cut tissues such as asparagus and celery ends.

Mechanical damage and physical injury, such as bruising, scratches and surface cuts, greatly accelerate the rate of water loss from fruit and vegetable tissue. Some tuber and root vegetables such as onions and potatoes retain the capacity to seal off wound areas after harvest when held at the appropriate temperatures and humidities (a process known as *curing*).

As mentioned earlier, respiration generates heat, which is dissipated through direct heat transfer to the environment and through evaporation of water. The heat of respiration raises the tissue temperature and therefore increases transpiration.

The ambient RH is not a very reliable guide to likely water loss and it is more useful to calculate the water vapor pressure deficit (WVPD) at the particular temperature and humidity. The WVPD of the air is defined as the difference between the water vapor pressure of the ambient air and that of saturated air at the same temperature (Ben-Yehoshua and Rodov, 2003). Thus, the drier the air, the greater the WVPD and the more rapidly any produce held in that environment will transpire. To minimize transpiration, produce should be held at low temperature, high RH and as small a WVPD as possible. Alternatively, packaging materials that have very low WVTRs can be used. However, the problem in these situations is that decay processes are favored.

18.2.3 Postharvest Decay

Once microorganisms are established in plant tissue, they can proliferate and secrete enzymes to bring about quality deterioration. Frequently, there is a lag period between infection and any manifestation of the presence of microorganisms. The most common pathogens causing harvested vegetables to rot are fungi such as *Alternaria*, *Botrytis*, *Diplodia*, *Monilinia*, *Penicillium*, *Phomopsis*, *Rhizopus* and *Sclerotinia* and the bacteria *Erwinia* and *Pseudomonas*. The majority of these can only invade damaged tissue such as bruised structures and fractured cells. The development of postharvest decay is favored by high temperatures and high humidities, with the latter often a result of condensation which may affect spore germination and can cause tissue anaerobiosis.

Acidic fruit tissue is generally attacked and rotted by fungi, while many vegetables with a tissue pH above 4.5 are more commonly attacked by bacteria. Initially only one or a few pathogens may invade and break down the tissues, followed by a broad spectrum attack of several weak pathogens which results in complete loss of the produce.

18.3 MODIFIED ATMOSPHERE PACKAGING OF FRESH HORTICULTURAL PRODUCE

18.3.1 Introduction

As stated earlier, a simple consideration of Equation 18.1 would suggest that if the CO_2 in the atmosphere were augmented (or the O_2 decreased), then the respiration rate would decrease and the shelf life would be extended. This is the basis of modified atmosphere packaging (MAP) as discussed in Chapter 16. The recommended concentrations of O_2 and CO_2 for fruits and vegetables can be found in the published literature, and a very effective way of plotting this data with CO_2 concentration as the ordinate and O_2 concentration as the abscissa is presented in Figures 18.1 and 18.2 (Kader et al., 1998). The windows represent the boundary of recommended gas concentrations; the smaller the window the more rigid the design requirement. Thompson (2010) reviewed the increase in shelf life for a wide range of fruit and vegetables packaged under MAP.

The permselectivity ratio β (permeability coefficients of CO_2:O_2) for air is ~0.8 (Table 18.6) and this is represented as line A–D in Figures 18.1 and 18.2. An otherwise impermeable package with a few small holes can be used to create atmospheres along this line; no vegetable windows fall on this line but it does pass through the window for berry fruits and figs. Line A–B is plotted for a β of 5.0 which is approximately the value for LDPE and PVdC copolymer films. This line bisects several windows indicating that these films could be used successfully for some fruits and vegetables.

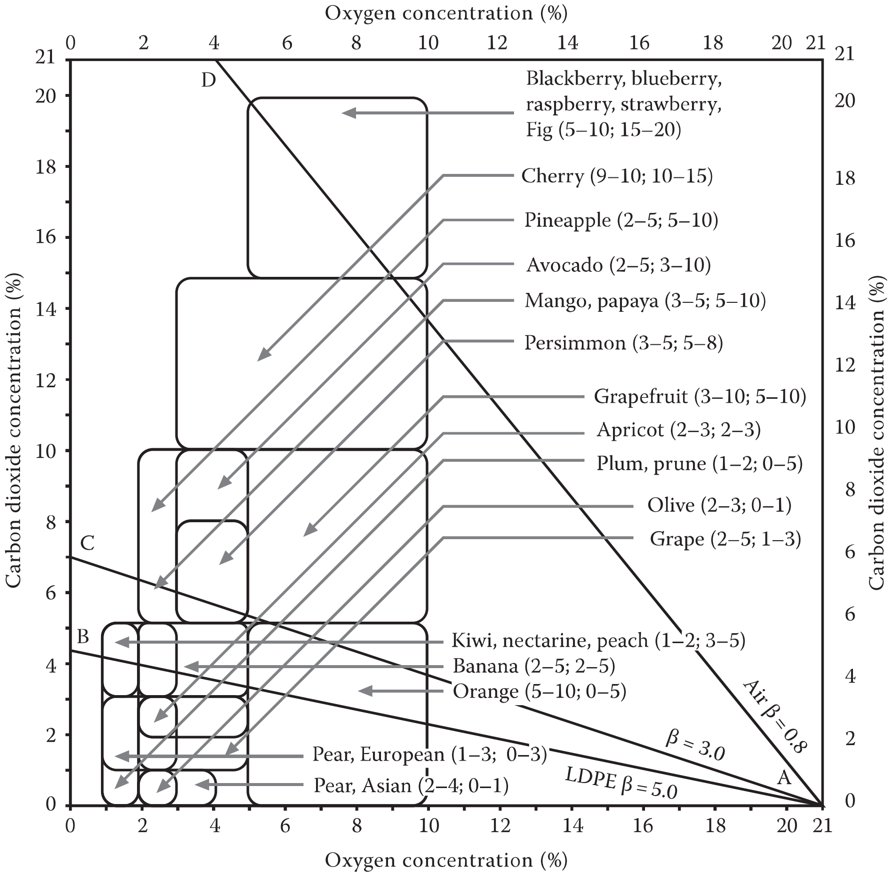

FIGURE 18.1 Recommended modified atmospheres for storage of fruits. (From Kader, A.A. et al., Technologies to extend the refrigerated shelf life of fresh fruits, in: *Food Storage Stability*, Taub, I.A. and Singh, R.P. (Eds), CRC Press, Boca Raton, FL, pp. 419–434, 1998).

However, PVdC copolymer is suitable only for produce with very low respiration rates because it has such low gas permeabilities (Table 18.6). The CO_2-O_2 atmospheres that lie between the lines A–B and A–D may be created by using packages made from LDPE film with perforations or microporous windows. The permselectivity ratios are not constant for a given polymer but increase as the temperature is lowered. For example, β for LDPE has been reported to range from 5.08 at 0°C to 3.45 at 20°C and β for PVC from 6.0 at 5°C to 4.0 at 40°C. Line A–C is plotted for a β of 3.0.

Since the 1960s, attempts have been made to create and maintain modified atmospheres within plastic polymeric films (Varoquaux and Ozdemir, 2005). As discussed in Chapter 15, the availability of absorbers of O_2, CO_2, C_2H_4 and water provides additional tools for the packaging technologist to use to maintain a desired atmosphere within a package. Details of such systems are now discussed.

18.3.2 FACTORS AFFECTING MAP

The conditions created and maintained within a package are the net result of the interplay among several factors, including those related to the specific fruit or vegetable and those related to the surrounding environment (Zagory, 1995).

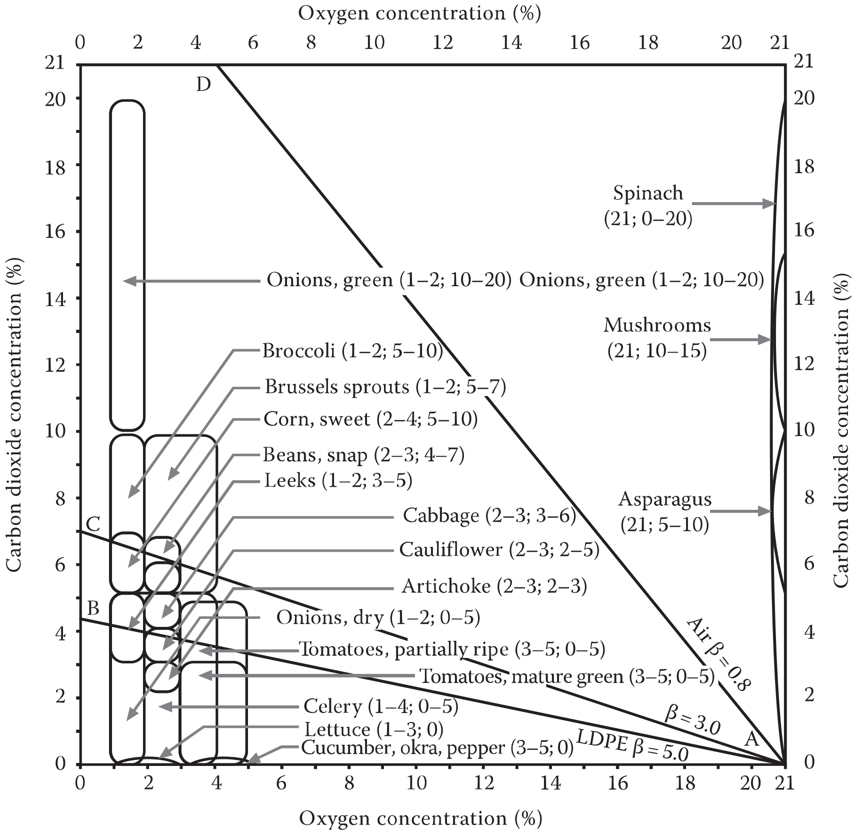

FIGURE 18.2 Recommended modified atmospheres for storage of vegetables. (From Kader, A.A. et al., Technologies to extend the refrigerated shelf life of fresh fruits, in: *Food Storage Stability*, Taub, I.A. and Singh, R.P. (Eds), CRC Press, Boca Raton, FL, pp. 419–434, 1998).

18.3.2.1 Resistance to Diffusion

Movement of O_2, CO_2 and C_2H_4 in fruit tissue occurs by diffusion of the gas molecules under a concentration gradient. O_2 in the environment immediately surrounding the external surface of the tissue diffuses in the gas phase through the dermal system and into the intercellular system; it then diffuses from the intercellular atmosphere into the cellular solution (cell sap) from where it diffuses in solution within the cell to centers of consumption. CO_2 and C_2H_4 produced in the cell sap diffuse outward to the ambient environment under a concentration gradient.

The rate of gas movement depends on the properties of the gas molecule, the magnitude of the gradient and the physical properties of the intervening barriers. Both the solubility and diffusivity of each gas are important for its diffusion across barriers, with CO_2 moving more readily than O_2; CO_2 and C_2H_4 have similar diffusion rates (Kader and Saltveit, 2003b).

Different commodities have different total amounts of internal air space; for example, potatoes have only 1%–2% while tomatoes have 15%–20% and apples have 25%–30%. A limited amount of air space could lead to a significant tissue resistance to gas diffusion. In addition, the cell wall appears to present some resistance to gas diffusion and thus a gradient between the cells and the intercellular space may be expected to develop (Kader et al., 1989).

Internal concentrations of O_2 and CO_2 in plant tissues depend on the stage of maturity at harvest, respiration rate, temperature, composition of the external atmosphere and added barriers (Kader and Saltveit, 2003b).

TABLE 18.6

Average Permeability Data[a] and Permselectivity Ratios of Some Polymeric Films, Air and Water to O_2 and CO_2 at 25°C and 5°C and 0% RH

	P in *barrer*		Permselectivity Ratio	Activation Energy E_P (kJ mol^{-1})	
Polymer	O_2	CO_2	β	O_2	CO_2
Low density polyethylene	4.9	21	4.3	43	39
	1.4	6.8	4.9		
High density polyethylene	0.9	3.1	3.4	35	30
	0.3	1.3	4.3		
Polypropylene	1.6	9.2	5.8	48	38
	0.4	3.1	7.8		
Poly(vinyl chloride) film	0.06	0.52	8.7	56	57
	0.01	0.10	10		
Poly(ethylene terephthalate)	0.13	0.26	2.0	38	28
(amorphous)	0.04	0.11	2.8		
(40% crystalline)	0.024	0.14	5.8	32	18
	0.009	0.08	8.9		
Poly(lactic acid) (98% *L*)	0.34	1.88	5.5	41	16
	0.10	1.18	11.8		
PVdC copolymer	0.006	0.029	4.8	67	52
	0.0009	0.006	6.7		
Perforated film (air)	2.5×10^7	1.9×10^7	0.76	3.6	3.6
	2.3×10^7	1.7×10^7	0.74		
Water	90	2.1×10^3	23.3	15.8	15.8
	57	1.3×10^3	22.8		

[a] Values taken from Table 4.3 and recalculated for 5°C using Equation 4.27.

A majority of studies on gas exchange in plant tissues indicate that the skin represents the main significant barrier to gas diffusion. Skin resistance to water vapor diffusion is much lower than resistance to O_2, CO_2 or C_2H_4 diffusion. As plant organs advance into the senescent stage, cell walls and membranes begin to break down, flooding some of the intercellular space with cell sap. In addition, the peel of some fruit may shrivel after prolonged exposure to lower water vapor concentrations. Consequently, the resistance of tissue to gas diffusion increases and may become significant (Kader et al., 1989).

18.3.2.2 Respiration

The respiration rate of a commodity inside a polymeric film package depends on the kind of commodity, its stage of maturity and physical condition, the concentrations of O_2, CO_2 and C_2H_4 inside the package, the quantity of product within the package, temperature and possibly light (Kader et al., 1989). These factors were discussed earlier in Section 18.2.1. Suffice it to say that the interplay of these factors leads to a complex situation about which it is difficult to make quantitative predictions (see Section 18.3.4).

18.3.2.3 Temperature

It is impossible to make any specific predictions about the magnitude of the effect of a change in temperature on MAP since a number of key, interrelated factors are involved. Any change in temperature will affect the respiration rate; it will also affect gas diffusion between the cell sap and the intercellular spaces, with the solubility of gases in liquids decreasing with increasing temperature. In addition, any change in temperature will affect the permeability of the plastic film surrounding the fruit or vegetable.

It is extremely unlikely that, as a result of any change in temperature, the change in respiration rate will match the change in gas permeability rates of the film. For a match to occur, the activation energy of permeation E_P would have to equal the activation energy of the respiration process and this is most unlikely. For example, Lakakul et al. (1999) reported, E_P for O_2 in LDPE as 37 kJ mol^{-1} and apparent E_A's for respiration of apple slices of 75 kJ mol^{-1} at 16 kPa O_2 and 55 kJ mol^{-1} at 0.5 kPa O_2, three times higher than for intact fruit. Exama et al. (1993) reported that E_A values for common fruits and vegetables in air range from 29.0 to 92.9 kJ mol^{-1}.

If the activation energies are not approximately equal, the equilibrium gas concentrations inside the package will change, which in turn will affect the respiration rate. If the temperature stabilizes, new equilibrium conditions will be established; however, if the temperature continues to change, steady-state conditions will never be reached. It is the complex nature of this dynamic situation that makes modeling of MAP so difficult (see Section 18.3.4).

18.3.3 METHODS OF CREATING MA CONDITIONS

The two methods for creating MA conditions are either passive or active and they were discussed in Chapter 16. Passive MA creation relies on the respiration of the produce and the gas permeability properties of the film to achieve the desired MA. Active MA creation involves gas flushing and gas scavenging technology by adding, for example, CO_2 and N_2, and/or removing O_2 during packaging. Although the passive method was the traditional approach taken with horticultural produce, the active approach is increasingly common. The main reason for this is the time required to achieve the desired MA: a week or longer may be necessary using the passive approach as shown in Figure 18.3. Such a delay is particularly unacceptable for fresh cut (minimally processed) produce where, for example, enzymic browning reactions need to be inhibited as soon as possible.

18.3.4 DESIGN OF MAPS

18.3.4.1 General Concepts

The selection of suitable packaging materials and the evaluation of MAP for fresh fruits and vegetables have traditionally been a largely empirical, trial-and-error exercise that is time-consuming, subjective and often without unifying principles to guide the research and development efforts. This empirical approach can lead to long testing times, high development costs, costly over packaging and the absence of a mechanism to fine-tune a packaging system once it has been developed. In an attempt to put the design of MAP on an analytical basis, a number of research groups have proposed and tested mathematical models (Yam and Lee, 1995; Mahajan et al., 2007) and these have been reviewed by Rodriguez-Aguilera and Oliveira (2009) and Zhang et al. (2011); few are used commercially. University College Cork in Ireland has developed the web-based software

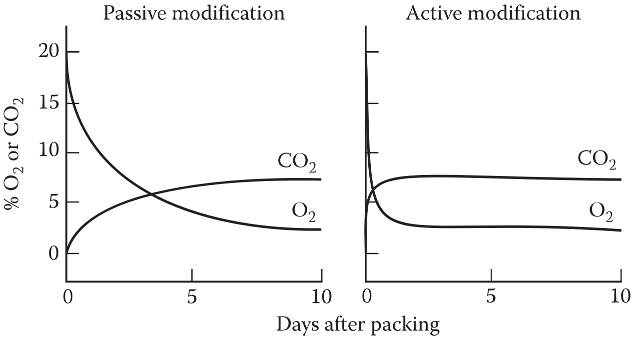

FIGURE 18.3 Relative changes in O_2 and CO_2 concentrations during passive modification and active modification of packaged horticultural products. (From Zagory, D. and Kader, A.A., *Food Technol.*, 42(9), 70, 1988).

tool PACK-in-MAP™ that helps in designing MAP for fresh and fresh-cut fruits and vegetables (www.packinmap.com). A practical software simulation tool to predict the amount of O_2 permeating into the package headspace during storage for a variety of multilayer packaging configurations was described by Van Bree et al. (2010).

In order to predict what the equilibrium gas concentrations will be and how long it will take to achieve equilibrium, a model should take into account the following factors (Zagory and Kader, 1988):

1. The effects of changing O_2 and CO_2 concentrations on the respiration rate
2. The possibility that the *RQ* is not equal to 1
3. The permeability of the film to O_2 and CO_2
4. The effect of temperature on film permeability
5. The surface area and headspace of the package
6. The resistance of the commodity to diffusion of gases through it
7. The optimal atmosphere for the commodity of interest
8. The gas concentrations which are likely to be deleterious to the commodity and if they are likely to be reached before or after equilibrium

The key part of any model is the relationship between the rate of respiration by the commodity and the permeation rate of respiratory gases through the package. As the O_2 supply within the plant cells begins to decrease as a result of respiration, the partial pressures of O_2 between the cells and the package interior and exterior atmospheres become unbalanced, causing some O_2 to diffuse into the package. When the rate of O_2 consumption exceeds the rate of O_2 permeation into the package, the O_2 concentration in the package decreases. This, in turn, further slows the respiration rate to the point where the rate of O_2 consumed equals the rate of O_2 permeation through the package film.

True equilibrium in the package would be reached when the gas flux due to respiration equaled the gas flux due to permeation; that is, O_2 was being consumed at the same rate at which it was entering the package, and CO_2 was being produced at the same rate at which it was leaving the package. However, unless the package is held under very closely controlled temperature conditions, it is doubtful if true equilibrium is ever achieved. This has not stopped some authors from referring to equilibrium MAP or EMAP when they mean the optimum or target atmosphere, for example, Del-Valle et al. (2009). Furthermore, since no polymeric film has the same permeability to O_2 as to CO_2, and because anoxic conditions and resultant anaerobic respiration are to be avoided at all costs, steady-state conditions inside a package are generally taken to be when the rate of O_2 consumption equals the rate of O_2 permeability through the film. In such situations, the concentration of CO_2 inside the package will increase over time, because the partial pressure difference of CO_2 across the package film will, at least in the early stages, be so low as to result in negligible gas flux to the external atmosphere.

The real challenge in designing and developing MA packages for fresh produce is to determine the O_2 consumption and CO_2 evolution rates under the variable atmosphere conditions existing in the package. These values can be found in the literature for many products under normal atmosphere but not under abnormal atmosphere conditions.

In examining the factors listed earlier, several important aspects must be remembered. The standard approach to measuring the gas permeabilities of films (see Chapter 4) uses Fick's law with some simplifying assumptions, the most salient in the present context being that there is a constant partial pressure difference across the film of the gas under consideration. Clearly, in MAP, this is not the case until (if ever) equilibrium is reached. Thus, the use of traditional film permeability data (if it is available at the temperatures of interest) to calculate likely gas fluxes will require accurate data on the pressure gradients across the package at any particular time.

18.3.4.2 Developing a Predictive Model

Because the shelf life of fresh horticultural produce can be extended by packaging in an atmosphere of reduced O_2 and elevated CO_2, it is of practical importance to be able to design a package to maintain the desired concentrations of O_2 and CO_2 inside a single retail package of fresh produce. A predictive model makes the design process more focused and rapid (Hertog and Banks, 2003).

The influx of O_2 and efflux of CO_2 at a specific temperature are determined by the permeability of the package, the thickness and surface area of the film, and the partial pressure gradients of O_2 and CO_2 inside and outside the package. The first three parameters should be specified by the designer of the package, while the partial pressure gradients are dictated by the desired atmospheric composition inside the package and the ambient atmosphere.

The starting point for the development of a predictive model for MAP is the application of Fick's law to the package system. From Equation 4.15, the flux of O_2 through a polymeric film can be described as follows:

$$Q_O = \frac{P_O}{X} A(p_{Oo} - p_{Oi}) \tag{18.3}$$

where

Q_O is the diffusive flux of O_2 through the package in unit time
P_O is the O_2 permeability coefficient of the package at the temperature of storage
A is the surface area of the package
X is the thickness of the film
p_{Oo} is the partial pressure of O_2 outside the package (0.209 atm)
p_{Oi} is the partial pressure of O_2 inside the package

A similar expression can be written for the flux of CO_2 through the package:

$$Q_C = \frac{P_C}{X} A(p_{Ci} - p_{Co}) \tag{18.4}$$

where

Q_C is the diffusive flux of CO_2 through the package in unit time
P_C is the CO_2 permeability coefficient of the package at the temperature of storage
p_{Ci} is the partial pressure of CO_2 inside the package
p_{Co} is the partial pressure of CO_2 outside the package (0.0003 atm but essentially zero)

The flux of O_2 into the fruit or vegetable is a function of the respiration rate (RR_O), which in turn is a function of the O_2 (and maybe CO_2) concentration within the package (Fonseca et al., 2002):

$$Q_f = RR_O W \tag{18.5}$$

where

Q_f is the flux of O_2 into the fruit per unit time
RR_O is the respiration rate or O_2 uptake of the fruit (mL kg^{-1} h^{-1}) as a function of O_2 partial pressure inside the package
W is the weight of fruit in the package

At equilibrium, the O_2 flux through the film and into the fruit should be equal; that is, $Q_O = Q_f$. On rearranging Equations 18.3 and 18.5,

$$\frac{P_O A}{X} = \frac{RR_O W}{(p_{Oo} - p_{Oi})} \tag{18.6}$$

Thus, Equation 18.6 enables the prediction of the O_2 permeability requirements provided RR_O, the relationship between the respiration rate and O_2 concentration, is known. Inspection of Equation 18.6 indicates that the equilibrium concentration of O_2 (p_{Oi}) is independent of time; this is understandable since the time to equilibrium depends on the free or headspace volume of the package. The smaller the free volume, the faster equilibrium or steady-state conditions are reached.

The effect of changing the surface area of the package or the weight of produce in the package can be calculated by rearranging Equation 18.6:

$$\frac{A}{W} = \frac{RR_O X}{P_O(p_{Oo} - p_{Oi})} \tag{18.7}$$

Similar calculations can be made to calculate the effect of changing the thickness of the film X.

A similar equation to Equation 18.6 can be derived for CO_2:

$$\frac{P_C A}{X} = \frac{RR_C W}{(p_{Ci} - p_{Co})} \tag{18.8}$$

Equations 18.6 and 18.8 can be rearranged to make A/WX the subject of each equation and then combined:

$$\frac{A}{WX} = \frac{RR_O}{P_O(p_{Oo} - p_{Oi})} = \frac{RR_C}{P_C(p_{Ci} - p_{Co})} \tag{18.9}$$

and

$$(p_{Ci} - p_{Co}) = \frac{P_O}{P_C}(p_{Oo} - p_{Oi})\frac{RR_C}{RR_O} \tag{18.10}$$

If gas concentrations (c), rather than partial pressures (p), are used (for example, 10% O_2 (v/v) = 0.1 atm = 10.13 kPa), RQ is the respiratory quotient RR_C/RR_O and the permselectivity ratio of P_C to P_O is designated as β, then

$$c_{Ci} = \frac{1}{\beta}(c_{Oo} - c_{Oi})RQ + c_{Co} \tag{18.11}$$

and

$$c_{Ci} = \left[c_{Co} + \frac{RQ}{\beta}c_{Oo}\right] - \frac{RQ}{\beta}c_{Oi} \tag{18.12}$$

For a specific film and RQ, the terms inside the bracket are all constant and there is a linear relationship between c_{Ci} and c_{Oi} with a slope equal to $-RQ/\beta$.

The intercept on the *y* axis can be calculated by letting $c_{\mathrm{Oi}} = 0$ and assuming that $RQ = 1$ and $\beta = 5$. Then,

$$c_{\mathrm{Ci}} = c_{\mathrm{Co}} + \frac{RQ}{\beta} c_{\mathrm{Oo}}$$

$$= 0.0003 + \frac{0.21}{5} = 0.0423 = 4.23\%.$$

Similarly, when $\beta = 0.8$,

$$c_{\mathrm{Ci}} = 0.0003 + \frac{0.21}{0.8} = 0.2628 = 26.3\%.$$

Using Equation 18.12, it is possible to construct lines for various β values. For example, for LDPE film where $\beta \approx 5$ at 5°C (Table 18.6) and assuming that $RQ = 1$, results in the straight lines A–B in Figures 18.1 and 18.2, both with a slope of −1/5. The implication is that only the modified atmospheres falling along the line A–B can be generated by LDPE film, for example, 2.2% CO_2 and 11% O_2, or 1.4% CO_2 and 16% O_2. Clearly the value of the respiratory quotient *RQ* affects the slope of the line A–B; *RQs* greater than unity will result in slopes greater than $-1/\beta$ and *vice versa*.

It is helpful to understand the importance of film thickness and surface area on MAP. Consideration of Equations 18.3 and 18.4 indicates that doubling the thickness of a film will halve the amount of gas that can move across the film in a given amount of time; making the film thinner will have the opposite effect. Once the β of the film is known, the thickness of the film will help determine where on the β line the actual gas concentrations in the package will lie (Figures 18.1 and 18.2). Increasing the thickness or decreasing the surface area of the film will move the gas equilibrium concentrations up the β line owing to reduced gas movement across the film. Increasing the weight of produce inside the package will have a similar effect because more produce will consume more O_2 and produce more CO_2.

The quantitative relationship between these factors can be expressed by rearranging Equation 18.6 and substituting concentrations for partial pressures:

$$P_{\mathrm{O}} = \frac{RR_{\mathrm{O}}WX}{A(c_{\mathrm{Oo}} - c_{\mathrm{Oi}})} \tag{18.13}$$

Equation 18.13 enables calculation of the desired permeability of a plastic film to supply sufficient O_2 to a product in order to prevent anaerobic conditions, provided the product respiration rate at the desired O_2 concentration is known; such data can often be found in the scientific literature (Zagory, 1995).

The aforementioned concepts were used in the development of a model to analyze the effect of the key parameters on the design of polymeric MA packages (Kader et al., 1998). The design parameters selected were *W*, *A*, *X*, P_{O} and P_{C}, the last three parameters being fixed when a specific film of given thickness is selected, leaving only *W* and *A* as design variables.

If the ratio *W*:*A* is denoted by τ, then Equations 18.6 and 18.8 can be rearranged to yield

$$c_{\mathrm{Oi}} = c_{\mathrm{Oo}} - \frac{XRR_{\mathrm{O}}}{P_{\mathrm{O}}} \tau \tag{18.14}$$

$$c_{\mathrm{Ci}} = c_{\mathrm{Co}} - \frac{XRR_{\mathrm{C}}}{P_{\mathrm{C}}} \tau \tag{18.15}$$

If the respiration rates do not change with gas concentrations, then any changes in τ simply move the gas compositions inside the package along the line A–B. As τ increases, the O_2 concentration decreases and the CO_2 concentration increases. Thus, the package atmosphere moves toward B on the line A–B in direct proportion to the increase in τ.

However, the respiration rate usually decreases as the package atmosphere moves toward B, and therefore the actual change in package atmosphere is smaller than that dictated by the increase in τ alone. Similarly, the effect of any decrease in τ will also be moderated. Therefore, the effect of any errors made in the selection of τ will be moderated to a large extent by the response of respiration rate to the change in package atmosphere (Kader et al., 1998).

Equation 18.6 can be rewritten as follows:

$$P_O = \frac{RR_O WX}{A(p_{Oo} - p_{Oi})} \tag{18.16}$$

Similarly for Equation 18.8:

$$P_C = \frac{RR_C WX}{A(p_{Co} - p_{Ci})} \tag{18.17}$$

Assuming that $RR_O = RR_C$ and substituting for P_O and P_C yields the following equation:

$$\beta = \frac{P_C}{P_O} = \frac{p_{Oo} - p_{Oi}}{p_{Ci} - p_{Co}} \tag{18.18}$$

If air surrounds the package, then p_{Oo} is approximately 0.21 atm and since p_{Co} is essentially zero, Equation 18.18 can be simplified to

$$\beta = \frac{0.21 - p_{Oi}}{p_{Ci}} \tag{18.19}$$

Table 18.6 lists average values for P_O and P_C and the corresponding β values for some common polymeric films as well as air and water. The values at 5°C were obtained from the values at 25°C using the appropriate activation energy for permeation E_P as the following example demonstrates.

Example 18.1

Equation 4.27 can be written for each temperature:

$$P_5 = P_o \exp\left(\frac{-E_p}{RT_5}\right)$$

$$P_{25} = P_o \exp\left(\frac{-E_p}{RT_{25}}\right)$$

On dividing the first equation by the second:

$$P_5 = P_{25} \exp\left(\frac{-E_p}{R\left[1/T_5 - 1/T_{25}\right]}\right)$$

The temperatures must be converted from °C to K:

$$\frac{1}{T_5} = \frac{1}{(273+5)} = \frac{1}{278} = 0.003597$$

$$\frac{1}{T_{25}} = \frac{1}{(273+25)} = \frac{1}{298} = 0.003356$$

To calculate the O_2 permeability of PVdC copolymer at 5°C and $E_P = 67{,}0000\ \mathrm{J\ mol^{-1}}$

$$P_5 = 0.006\ \exp\left(\frac{-67{,}000}{8.314\left[0.003597 - 0.003356\right]}\right)$$

$$= 0.006\ \exp(-8059 \times 0.000241)$$

$$= 0.006\ \exp(-1.9422)$$

$$= 0.006 \times 0.1434$$

$$= 8.6 \times 10^{-4}\ \mathit{barrer}$$

That is, *P* is seven times greater at 25°C than at 5°C.

Example 18.2

Assume that a company wanted to package sweet corn in a MA and store it at 5°C. From Figure 18.2, the optimum atmosphere is 2%–4% O_2 and 5%–10% CO_2. Taking the midpoint concentrations for both gases and substituting in Equation 18.19:

$$\beta = \frac{0.21 - p_{\mathrm{Oi}}}{p_{\mathrm{Ci}}} = \frac{0.21 - 0.03}{0.075} = 2.4 \tag{18.20}$$

From Table 18.6, it can be seen that at 5°C there are no films that have a β value of 2.4, although amorphous PET is close at 2.8. If the β value is recalculated for 2% O_2 and 5% CO_2, a value of 3.8 is obtained; for 4% O_2 and 10% CO_2, the β value is 1.7. Given this wide range of values for β, it is clear that such calculations provide only a rough guide to selecting suitable films for MAP of fruits and vegetables. Once a candidate film has been selected, trials are required to confirm the choice and ensure that the desired atmospheres are in fact achieved.

In the case where the film has similar permeability coefficients to both O_2 and CO_2 (i.e., β = 1), the sum of the partial pressures of O_2 and CO_2 inside the package will equal 0.21 atm. The final volume concentrations of O_2 and CO_2 inside the package will be ~21%, the exact value depending on the *RQ* of the product. Therefore, products requiring optimum atmospheres of say 5% O_2 and 15% CO_2 could achieve this by using a perforated package. From Figure 18.1, it can be seen that blackberries, blueberries, figs, raspberries, strawberries and cherries are suitable for packing in perforated packages.

However, because in reality the permeability coefficients of commercial films are different for O_2 and CO_2 (P_C is typically 3–6 times P_O as shown in Table 18.6), the sum of the partial pressures will be less than 0.21 atm. Although the partial pressure of CO_2 inside the package increases and the partial pressure of O_2 decreases, the total pressure of these two gases will be less than 0.21 atm. Given that according to the gas laws, the total pressure times the volume is a constant, the volume of the package will decrease. As the volume of the package decreases, the partial pressure of N_2 inside the package will exceed the partial pressure of N_2 outside. This results in the permeation of N_2 through the package to the outside and, in certain situations, the reduction in package volume is such that the film adheres to the surface of the fruit or vegetable. In other situations, such as the onset of anaerobic respiration where there is a rapid buildup of CO_2, the total pressure inside the package may increase, causing the package to bulge. This would cause the partial pressure of both O_2 and N_2 inside the package to decrease and favor permeation of these gases into the package. The actual scenario depends on whether the package is rigid or flexible. In a rigid package, the free volume remains constant, while the total pressure may change, whereas in a perfectly flexible package, the total pressure remains constant while the free volume may change (Talasila and Cameron, 1997).

It is not only the permselectivity ratio which is important, but also the actual magnitude of the permeability values. If the permeability coefficients are very small, then the gas fluxes will be very low and there is the possibility of anoxic conditions or undesirably high concentrations of CO_2 developing inside the package.

As is evident from Table 18.6, the β value for a particular film is not constant but varies with temperature; the higher the temperature, the lower the β value. In a study based on 122 permeability measurements of LDPE film, β values at 0°C, 5°C, 10°C, 15°C and 20°C were 5.08, 4.63, 4.16, 3.79 and 3.45, respectively; data from eight other film types (not specified) showed that, with one exception, the ratios increased as the temperatures decreased toward 0°C (Tolle, 1971). As many authors have noted, there is a dearth of actual film permeability values at the temperatures and humidities likely to be encountered during storage of MAP horticultural produce.

Another important variable can be the free or headspace volume of the package. In converting concentration measurements into volume of gases, it is usually assumed that the total pressure in the enclosed system is constant over time. However, this is true only when the *RQ* of the produce is unity. As was discussed earlier, this is certainly not always the case in MAP of fresh produce.

For models such as that described earlier to be widely applicable, a great deal of data is required, including the permeances of potentially useful films at likely storage temperatures and the relationship between the rate of respiration and O_2 concentration. It is also necessary to have similar data for CO_2 so that the potentially damaging effects of high CO_2 concentrations on produce quality can be avoided. Even with all this data, the reality is that few polymeric films are capable of maintaining the desired MAs. That is why perforated films and, more recently, films with an adjustable selectivity for CO_2 and O_2 and permeability that increases dramatically as temperature increases (Clarke, 2011), have been developed.

18.4 PACKAGING OF HORTICULTURAL PRODUCTS

18.4.1 Fresh and Minimally Processed Horticultural Produce

18.4.1.1 Introduction

The quality of fruits and vegetables comprises several parameters including flavor, aroma, texture, appearance, nutrition and safety, and the relative importance of each parameter depends on the particular commodity and its intended use. The quality of the produce is compromised whenever one of these parameters falls below a certain desirable level. The most important aspect of produce quality is freshness, typified by the quality of a fruit or vegetable when it is freshly harvested (Cardello and Schutz, 2003). Fresh fruits and vegetables are expected to be crisp, not tough, sweet (where appropriate), juicy, nutritious and free from defects (Zagory, 1995). The challenge is to maintain these properties of freshness during long transportation and marketing periods and packaging has a key role to play here.

In addition to maintaining freshness, modern retail packaging of fresh horticultural produce is expected to meet a wide range of requirements including prevention of mechanical damage resulting from handling, compression and impact; minimization of weight loss and shrinkage and, if the produce is at ambient temperature at the time of packing, the ability to cool the produce rapidly after packing.

Minimally processed fruits and vegetables (MPFVs) are products that have the attributes of convenience and fresh-like quality, and their forms vary widely depending on the nature of the unprocessed commodity and how it is normally consumed. They are increasingly referred to as *fresh-cut* produce, defined as any fresh fruit or vegetable or any combination thereof that has been physically altered from its original form but remains in a fresh state (Lamkanra, 2002). MPFVs have gained a significant proportion of the fresh produce market since their introduction to the U.S. market in the 1970s and to European markets in the 1980s. The purpose of minimal processing is to deliver to the consumer a like-fresh product with an extended shelf life, while simultaneously maintaining the nutritional and sensory quality and ensuring food safety.

MPFVs remain biologically and physiologically active and this results in increased metabolic activity including increased respiration rates. In some cases, C_2H_4 production may also increase. The physiology of minimally processed products is essentially that of wounded tissues as a result of mechanical injury resulting from processes such as cutting, trimming and peeling. Wounding of tissues induces a number of physiological disorders that need to be minimized to get fresh-like quality products. The intensity of the wound response is affected by a great number of factors, the most significant being species and variety, O_2 and CO_2 concentrations, water vapor pressure and the presence of inhibitors.

Of key importance with MPFVs is the control of enzymes, either endogenous from the produce itself or exogenous from invading microorganisms, to maintain the firm, crisp texture and bright, light color. The enzymes can be controlled by inactivation or chemical or physical means. Methods that are currently used include temperature, MAs, very high pressures and chemicals such as ascorbic acid, vanillin (which inhibits polygalacturonase), mannose (which reduces C_2H_4 production, respiration and softening in pears) and gases such as SO_2, CO and ethylene oxide. However, it is unlikely that the widespread use of the latter three gases would ever gain regulatory approval or meet with consumer acceptance given the current trend toward additive-free food.

Enzymic browning caused by polyphenoloxidase (PPO) is often the major concern related to shelf life extension of fresh-cut fruit and strongly affects the consumer's purchase decision. Although sulfites were traditionally used for browning prevention, their use on fresh-cut fruit and vegetables was banned in 1986 by the FDA owing to their potential health hazards. Various alternative approaches have been investigated including reducing agents such as citric acid, ascorbic acid, isoascorbic acid and sodium erythorbate, and thiol-containing amino acids such as *N*-acetylcysteine and glutathione, oxalic acid and 4-hexylresorcinol. Calcium treatments can maintain or improve tissue firmness and crispness of fresh-cut fruit, and $CaCl_2$ has been one of the most frequently used salts although it is reported to impart residual taste to the product. Thus, other calcium salts such as calcium lactate, calcium propionate or calcium ascorbate have been investigated as alternative sources of calcium (Oms-Oliu et al., 2010). The application of edible coatings to deliver active substances is one of the recent major advances made in order to increase the shelf life of fresh-cut produce. Edible coatings also decrease WVTR by forming a barrier on the fruit surface, preventing loss of water and turgor.

Microbial deterioration of MPFV can be controlled by several methods including the use of chill temperatures, reduction of the total microbial population by the use of heat or irradiation and the use of antagonistic organisms that control growth of undesirable microorganisms (Novak, 2010). Antimicrobial agents such as plant essential oils have been introduced as a novel way to improve microbiological stability of fresh-cut fruit (Oms-Oliu et al., 2010). The use of sanitizing chemicals such as chlorine, ozone, chlorine dioxide and peroxyacetic acid in chilled wash water are approved for use on fresh produce.

18.4.1.2 Packaging Materials

At the outset, it must be recognized that fresh produce is not a single commodity since there are hundreds of different fruits and vegetables, each with their own particular requirements for package performance. There have been some publications on the packaging of MPFVs, and generally the same packaging processes are used as for fresh produce. However, allowance has to be made for differences in the respiration rate of produce which has been processed in some way. There is an increasing trend away from heavily processed toward MPFVs, and although some research has been undertaken to develop the most effective packaging systems, more is required.

Normally, a shelf life for packaged fresh produce and MPFVs of at least 7 days at refrigerated conditions (≤5°C) is required, and to achieve this, MAP is usually necessary. The primary spoilage mechanisms are the metabolism of the tissue and microbial growth; both will cause deterioration of the tissue and must be controlled to maintain tissue viability. Generally, the shelf life of MPFVs is inversely proportional to respiration rate. Microbial spoilage has become a major reason for sensory quality shelf life failure for most packaged MPFVs, followed by surface discoloration (e.g., pinking of cut lettuce, browning of cut potato, greying and browning of processed pineapple and grey discoloration of cabbage), water-soaked appearance or translucency (e.g., cut watermelon, papaya, honeydew and tomatoes), moisture loss (e.g., "baby" carrots and celery sticks), off-aroma (e.g., broccoli florets and diced cabbage in low O_2 and high CO_2 atmospheres), flavor changes (e.g., cut kiwifruit) and texture changes (e.g., processed strawberry, grated celery, kiwifruit and papaya). Microbial spoilage including formation of off-flavors (e.g., fermented aroma with cut lettuce, sour taste with cantaloupe and bell pepper), slimy surface (e.g., "baby" carrots), wetness and soft rot (e.g., cut bell pepper), discoloration (e.g., apple wedges) and visual microbial growth/colonies (such as apple wedges, cantaloupe chunks and cored pineapple) has been used as a main or exclusive objective criterion to determine shelf life of fresh-cut products (Barth et al., 2009).

Chill temperatures during storage, dipping in anti-browning solutions and MAP are the most common approaches used to preserve the initial color of MPFVs (Zhuang et al., 2011). Ascorbic acid (AA) and its derivatives have been used in numerous studies in fruits in concentrations ranging from 0.5% to 4%. Recently, Mastromatteo et al. (2011) reported on the effectiveness of different strategies to prolong the shelf life of minimally processed kiwifruit. The use of active MAP (10% O_2 and 10% CO_2) together with a sodium alginate coating to control dehydration and respiration gave a shelf life of up to 13 days at 5°C. The OPP bags of 20 μm thickness used had an OTR at 5°C of 1015 mL m^{-2} day^{-1} and CDTR of 2700 mL m^{-2} day^{-1} (i.e., $\beta \approx 2.7$).

The beneficial effects of MAP for MPFVs have been reviewed (Solomos, 1997; Ahvenainen, 2000). Depleted O_2 or enriched CO_2 levels reduce respiration and decrease C_2H_4 production, inhibit or delay enzymic reactions, alleviate physiological disorders and preserve the product from quality losses. However, exposure to O_2 or CO_2 levels outside the limits of tolerance may lead to anaerobic respiration with the production of undesirable metabolites and other physiological disorders. Nevertheless, the levels of O_2 and CO_2 required to avoid tissue damage or quality loss are unknown for most fruits and vegetables. Low O_2 atmospheres act synergistically with elevated CO_2 levels to reduce C_2H_4 production and respiration rates but do not completely stop senescence and tissue breakdown.

In what at first seems counterintuitive, high O_2 MAP (>60 kPa) has been found to be effective at inhibiting enzymic browning, preventing anaerobic fermentation and inhibiting aerobic and anaerobic microbial growth, possibly as a result of the generation of reactive oxygen species (O_2^-, H_2O_2, $OH^\bullet$) in plant cells that damage vital cell components and thereby reduce cell viability (Jacxsens et al., 2001; Day, 2003). Target gas concentrations immediately after packaging are 80%–95% O_2 and 5%–20% N_2, the aim being to achieve O_2 levels >40% and CO_2 levels 10%–25% throughout chilled storage. A concern with this technology is potential worker safety implications during packaging in the production environment as O_2 concentrations higher than 25% are explosive (Barth et al., 2009). High O_2 barrier films are not suitable; the recommended film is 30 μm OPP.

Oms-Oliu et al. (2008) compared high O_2 (70 kPa) and low O_2 (2.5 kPa) active MAP to traditional passive MAP for fresh-cut pears at 4°C. High O_2 did not prevent the production of acetaldehyde and ethanol during storage but their accumulation was promoted under anoxic conditions. Although low O_2 reduced CO_2 production and inhibited C_2H_4 production, moderate CO_2 concentrations in combination with excessively low O_2 levels inside packages accelerated the accumulation of fermentative metabolites. Both low and high O_2 significantly reduced the growth of microorganisms during storage. Recently, Liu et al. (2010) reported on changes in the quality of mushrooms stored at 2°C for 12 days under 100% and 80% O_2 atmospheres and air. The respiration rate was suppressed in the O_2 atmospheres, and no significant differences were found between 80% and 100% O_2. Weight loss and firmness of mushrooms held in high O_2 were significantly higher than in air, and high O_2, especially 100% O_2, was effective at inhibiting discoloration.

Polymeric films are the most common materials used for the packaging of horticultural products including MPFVs (Toivonen et al., 2009). Early work in the area stressed the primary role of packaging to reduce transpiration, with many studies encouraging film perforation to avoid the development of injurious atmospheres inside the packages. In addition to enabling the creation of MA conditions, polymeric films provide other benefits including maintenance of high RH and reduction of water loss; improved sanitation by reducing contamination during handling; minimal surface abrasions by avoiding contact between the commodity and the shipping container; reduced spread of decay from one produce item to another; use of the film as a carrier of fungicides, scald inhibitors, C_2H_4 absorbers or other chemicals; facilitation of brand identification and providing relevant information to consumers (Kader and Watkins, 2000).

In packages where it is not intended to create a MA, the main concern is to avoid anoxic conditions and condensation of water vapor inside the package. This is most easily achieved either by incomplete sealing or perforation of the plastic packaging.

The relative effect of diffusive flow through holes on package atmosphere can be appreciated by comparing the permeability of gases in air with permeability of the gases in polymers as shown in Table 18.6. Air is much more permeable than polymeric films, so that even a very small hole in a polymeric package can affect the package atmosphere very significantly. This phenomenon is used to advantage with perforated films where the gas permeation can be adjusted by changing the dimensions of the perforations (see Table 4.1). In addition, perforated MAP can effectively reduce the humidity inside the package.

Rennie and Tavoularis (2009) demonstrated the feasibility of modeling perforation-mediated MAP based primarily on fundamental laws that accounted for all the major transport phenomena during storage of fresh commodities. The model can be used for steady-state as well as transient analysis of MAP in a wide variety of circumstances and could prove to be useful in risk analysis studies. Transpiration and condensation, which are often disregarded in models of MAP, were modeled to gain insight into a process that is very hard to investigate experimentally. The results indicated that the majority of the water vapor that is transpired eventually condenses on the package walls or on the commodity. They also showed that the assumption that the product temperature and the storage room temperature are equivalent, a common assumption in many models, could lead to errors in the prediction of the gas concentrations. Their results demonstrated the importance of obtaining accurate respiration rate data for the given variety and the actual conditions of the stored commodity. The sensitivity of the model to variations in the respiration rate for a given respiration rate model were tested by increasing or decreasing the respiration rate by 10%. These changes were found to have a significant effect on the steady-state gas concentrations. Because such variations in respiration rate occur regularly for most commodities, it indicates that, in practical situations, one should not expect to predict precise steady-state gas concentrations for MAP.

González-Buesa et al. (2009) proposed a model for describing the change in gas composition in packages of constant volume with microperforations of varying number and size, taking into account the dependency of the RR on gas composition and hydrodynamic flow through the microperforations. The change in gas composition inside the package predicted by the model was compared with the results of experiments conducted at 4°C with minimally processed peaches, fresh-cut cauliflower and whole black truffle, using seven packages with different numbers (0–14) and sizes (from $90 \times 50\,\mu m$ to $300 \times 100\,\mu m$) of microperforations. The experimental data and those predicted by the model showed a satisfactory agreement for O_2, but the CO_2 was underestimated for products with $RQ < 1$ but in agreement when $RQ > 1$.

The effect of thin layers and droplets of water on the inside surface of films can also be appreciated by reference to Table 18.6, which shows that the permeability of gases is much higher in water than in polymers. As a result, thin layers and droplets of water forming inside polymeric packages do not significantly affect the gas atmosphere in the package (Kader et al., 1998).

TABLE 18.7
Packaging Materials for Vegetables

Vegetable	Packaging Material and Thickness
Peeled potato, both whole and sliced	LDPE, 50 µm (also PA-LDPE, 70–100 µm or comparable)
Grated carrot	OPP, 40 µm, microperforated LDPE-EVA-OPP, 30–40 µm
Sliced swede	LDPE, 50 µm
Grated swede	LDPE-EVA-OPP, 40 µm
Sliced beetroot	LDPE, 50 µm (also PA-LDPE, 70–100 µm or comparable)
Grated beetroot	OPP, 40 µm, microperforated OPP, PE EVA-OPP, 30–40 µm
Shredded Chinese cabbage	OPP, 40 µm, LDPE-EVA-OPP, 30–40 µm
Shredded white cabbage	OPP, 40 µm, LDPE/EVA/OPP, 30–40 µm
Shredded onion	OPP, 40 µm (also PA-LDPE, 70–100 µm or comparable)
Shredded leek	LDPE, 50 µm, OPP 40 µm (also PA-LDPE, 70–100 µm or comparable)

Source: From Laurile, E. and Ahvenainen, R., Minimal processing in practice; fresh fruits and vegetables, in: *Minimal Processing Technologies in the Food Industry*, Ohlsson, T. and Bengtsson, N. (Eds), CRC Press, Boca Raton, FL, pp. 219–244, 2002.

Flexible packaging is the most common format for fresh-cut produce MAP and is available as preformed bags, roll stock and standup pouches. Rigid packaging formats consist of a rigid tray or container that may be designed as a clamshell, have a snap-on lid or a sealable, easy-peel lidding film (Toivonen et al., 2009). Many polymeric films are available for packaging purposes, and those most likely to be suitable include laminated or coextruded materials consisting of blends of LLDPE, LDPE or OPP with EVA copolymer. The polyolefin resins provide excellent strength and are good moisture barriers, while the EVA copolymer provides sealability and a higher O_2 permeability than the pure polyolefin resins. Table 18.7 gives details of packaging materials that have been suggested for MPVs. The O_2 and CO_2 permeabilities of the aforementioned films are required at actual conditions of use, but regrettably such data are scant, making the development of suitable packages a trial-and-error exercise in many cases. The use of such information was illustrated in Section 18.3.4.

As illustrated in Figures 18.1 and 18.2, there are some fruits and vegetables for which LDPE film will never be suitable if the optimum MAP is required. Thus, there is a need for modification of the permeability properties of the common polymeric films to make them more suitable for MAP and developments in this area have already been referred to in Section 5.9. Approaches adopted have included inorganic fillers, perforations and porous patches with a breathable membrane that has an adjustable selectivity for CO_2 and O_2 and permeability that increases dramatically as temperature increases (Clarke, 2011); they were described in Section 15.3.4.

The use of Ar in MAP was discussed in Chapter 16. Recommended MAP of salads using Ar is 70%–90% Ar, 0%–20% CO_2 and 1%–15% O_2 (Spencer and Humphreys, 2003). Over an average 5-day shelf life, O_2 levels declined from 10% to 15% toward 0%, while CO_2 levels rose from an initial 5%–15% to 20%–30% at the end of shelf life. Although increasing concentrations of CO_2 can extend the shelf life, there are undesirable side effects including bleaching of color, generation of off-tastes and deliquescence (dissolving of CO_2 in water), particularly in colored produce such as carrots and red cabbage. The use of Ar rather than N_2 slowed degradation by inhibition of oxidases from both product and microbial sources, with the total viable count being 40% less (Spencer and Humphreys, 2003).

18.4.1.3 Safety of MAP Produce

The general safety aspects of MAP were discussed in Chapter 16. In this section, specific comments relating to MAP of fruits and vegetables are discussed. For a more detailed discussion the reader is referred to Farber et al. (2003), Hui and Nip (2004), Raybaudi-Massilia et al. (2009), Barth et al. (2009) and Ragaert et al. (2011).

It is generally believed that with the use of permeable films, spoilage will occur before toxin production is an issue. However, MAP of produce should always incorporate packaging materials that will not lead to an anoxic package environment when the product is stored at the intended temperature; that is, high O_2 barrier films should not be used. The microorganisms that exist on the surfaces of raw, whole produce appear to be the major source of microbial contamination and consequent spoilage of fresh-cut fruits and vegetables. Fresh-cut products can also be contaminated by spoilage microorganisms through contact with people or equipment during processing and possibly by air during processing and packaging steps, especially in facilities that have been used for produce processing over an extended period of time (Barth et al., 2009). The elimination or significant inhibition of spoilage microorganisms should not be practiced, as their interaction with pathogens may play an integral role in product safety (Farber et al., 2003).

The commonly encountered spoilage bacteria of fruits and vegetables include *Pseudomonas* spp., *Erwinia herbicola*, *Flavobacterium*, *Xanthomonas*, *Enterobacter agglomerans*, lactic acid bacteria such as *Leuconostoc mesenteroides* and *Lactobacillus* spp. (Nguyen-the and Carlin, 1994). Certain common molds such as *Penicillium* spp., *Aspergillus* spp., *Eurotium* spp., *Alternaria* spp., *Cladosporium* spp., *Paecilomyces* spp. and *Botrytis* spp. have been shown to be involved in the spoilage of fresh fruits, as well as yeasts such as *Saccharomyces* spp., *Cryptococcus* spp. and *Rhodotorula* spp. Although this microflora is largely responsible for the spoilage of fresh produce, it can vary greatly for each product and storage conditions. Temperature can play a large role in determining the outcome of the final microflora found on refrigerated fruits and vegetables, leading to a selection for psychrotrophs and a decrease in the number of mesophilic microorganisms.

The effect of MAP on lactic acid bacteria can vary depending on the type of produce packaged. The increased CO_2 and decreased O_2 concentrations used in MAP generally favor the growth of lactic acid bacteria. This can expedite the spoilage of produce sensitive to lactic acid bacteria, such as lettuce, chicory leaves and carrots (Nguyen-the and Carlin, 1994). The effect of MAP on yeasts is negligible, but because molds are aerobic microorganisms, CO_2 can cause growth inhibition at concentrations as low as 10% (Molin, 2000). The antimicrobial properties of high CO_2 concentrations are mostly due to a reduction of pH and interference with the cellular metabolism.

The concern when using MAP for fruits and vegetables arises from the potential for foodborne pathogens, which may be resistant to moderate to high levels of CO_2 ($\leq 50\%$), to outgrow spoilage microorganisms, which may be sensitive to the MA. High levels of O_2 can inhibit the growth of both anaerobic and aerobic microorganisms because the optimal O_2 level for growth (21% for aerobes, 0%–2% for anaerobes) is surpassed. However, there have also been reports of high O_2 (i.e., 80%–90%) stimulating the growth of foodborne pathogens such as *Escherichia coli* and *Listeria monocytogenes* (Amanatidou et al., 1999).

Atmospheres with low O_2 levels inhibit the growth of most aerobic spoilage microorganisms which usually warn consumers of spoilage, while the growth of pathogens, especially the anaerobic psychrotrophic, nonproteolytic Clostridia, may be allowed or even stimulated. However, there have been few studies on the effect of MAP conditions on the microbial safety and stability of fresh-cut fruits.

At extremely low O_2 levels (<1%), anaerobic respiration can occur, resulting in tissue destruction and the production of substances that contribute to off-flavors and off-odors, as well as the potential for growth of foodborne pathogens such as *Clostridium botulinum* (Austin et al., 1998). The absence of outbreaks of botulism linked to MAP produce indicates that *C. botulinum* may be competitively inhibited under the packaging and resident flora conditions of these products. However, more research needs to be done to examine the potential for growth of *C. botulinum* in a wide variety of MAP produce stored at mildly abusive temperatures such as 7°C–12°C. In addition, it has been suggested that other hurdles besides temperature need to be examined to prevent botulinum toxin production (Farber et al., 2003).

Concerns about possible pathogen contamination in MAP produce have focused on *L. monocytogenes* owing to its ability to grow at refrigeration temperatures and remain largely unaffected by MAP while the normal microflora is inhibited (Amanatidou et al., 1999). Thus, although MAP produce can remain organoleptically acceptable, *L. monocytogenes* with a reduced microflora can grow at low temperatures (especially if low levels of lactic acid bacteria are present) to reach potentially harmful levels during the extended storage life of MAP produce (Farber et al., 2003).

Although edible biodegradable coatings are gaining in popularity, a number of problems have been associated with their use. For example, modification of the internal gas composition of the product due to high CO_2 and low O_2 can cause problems such as anaerobic fermentation of apples and bananas, rapid weight loss of tomatoes, elevated levels of core flush for apples, rapid decay in cucumbers and so on. Edible films can create very low O_2 environments where anaerobic pathogens such as *C. botulinum* may thrive, although antimicrobial compounds can be incorporated into the coating in this scenario if legislation permits. Because the antimicrobial or antioxidant can be incorporated and applied directly to the surface of the product, only small quantities are required.

Increasing food safety concerns of losing the biological structure that normally prevents harmful microorganisms from colonizing on food have been raised (Chuang, 2011). Because of the exposed tissue, MPFVs may be more susceptible to colonization by pathogenic bacteria than intact produce, owing to higher availability of nutrients on cut surfaces and greater potential for contamination because of increased handling. The efficacy of MAP to control the physiological decay of fresh-cut fruits warrants further investigation, and knowledge about the influence of MAP on the microbiological safety of these foods is still judged as inadequate by experts (Farber et al., 2003). The emergence of psychrotrophic pathogens such as *L. monocytogenes*, *Aeromonas hydrophila* and *Yersinia enterocolitica*, mesophiles such as *Salmonella* spp., *Staphylococcus* spp. and the microaerophilic *Campylobacter jejuni* is of greatest concern and further investigation is warranted. Despite these concerns, MAP of horticultural produce is now widespread with extremely few food poisoning outbreaks (Hui and Nip, 2004).

Ready-to-eat (RTE) packaged lettuce salads have been implicated in several salmonellosis outbreaks. The survival and growth of *Salmonella* spp., *E. coli* O157:H7 and *L. monocytogenes* inoculated onto shredded lettuce was determined under passive MAP and in air by Oliveira et al. (2010). After pathogen inoculation, the lettuce was packaged into two OPP films of different permeability and stored at 5°C and 25°C. After 10 days at 5°C, populations of *E. coli* O157:H7 and *Salmonella* decreased by ~1 log unit while *L. monocytogenes* increased by about 1 log unit in both package films. At 25°C, the level of pathogens increased between 2.4 and 4.2 log units after 3 days. Psychrotrophic and mesophilic bacteria had similar growth at both temperatures with higher populations in air than in the MAs. The composition of the MAs had no significant effect on the survival and growth of the pathogens at refrigeration temperatures. *L. monocytogenes* inoculated at low dose reached populations >100 cfu g^{-1} at 5°C. These results reinforce the necessity to avoid contamination of vegetables during packing, storage and handling, because if minimally processed vegetables become contaminated with these pathogens, they will be able to grow and survive if the product is not kept at refrigerated conditions.

Recently, Horev et al. (2012) reported on the effects of MAP on indigenous microbial populations and the survival of *Salmonella enterica* on the surface of romaine lettuce. Chlorine-washed lettuce leaves were inoculated with *S. enterica* serotype Typhimurium and packaged in one of three systems: (1) passive MAP in LDPE bags, (2) active MAP in the same bags with a gas mixture of 10% O_2, 10% CO_2 and 80% N_2 and (3) control without MAP. The active MAP had an antimicrobial effect on indigenous lettuce microflora, but not on *Salmonella* and even favored the survival of the pathogen, possibly due to the elimination of its natural antagonists. The effects of the passive MAP were less pronounced. The results obtained draw attention to potential safety risks of ready-to-eat fresh produce kept in active MAP and require further investigation.

In some countries, temperature abuse is a widespread problem in the distribution chain and can occur at any of the stages from storage through transportation to retail display and consumer handling.

In these situations, it is advisable to restrict the shelf life so that psychrotrophic pathogens have insufficient time to multiply and produce toxin. Where the shelf life is greater than 10 days and the storage temperature is likely to exceed 3°C, it has been suggested (Laurile and Ahvenainen, 2002) that the products should meet one or more of the following controlling factors:

- A minimum heat treatment such as 90°C for 10 min
- A pH of 5 or less throughout the food
- A salt level of 3.5% (aqueous) throughout the food
- a_w of 0.97 or less throughout the food
- Any combination of heat and preservative factors which has been shown to prevent growth of toxin production by *C. botulinum*

However, given that the aim is to maintain the freshness of MPFVs, the aforementioned treatments are not practicable and limiting the shelf life is the best solution.

Barth et al. (2009) identified the need for investigation of spoilage patterns and microflora of fresh-cut products packaged with new, emerging MAP technologies, including antimicrobial packaging, microperforated packaging, Breatheway® membrane packaging and high O_2 backflush, in commercial practice. With the continuing development of packaging technologies and changes in marketing fresh and fresh-cut produce, the spoilage microflora of packaged produce in the future may be completely different from today. For example, the headspace gas concentrations of fresh-cut produce in microperforated packages are significantly different from those packaged with conventional films. There is very limited information regarding how changes in atmospheric composition affect the spoilage microflora profile during refrigerated storage.

Fresh-cut produce has an extraordinary record of safety when the number of portions sold and consumed worldwide is considered. Nevertheless, there have been many outbreaks associated with bagged, fresh-cut produce, especially salads and leafy greens. It is unclear if there is a higher incidence of foodborne illness associated with bagged cut produce than with whole commodity produce, or if outbreaks are merely larger, more often detected and more prominent (O'Beirne and Zagory, 2009). When outbreaks do occur, suspicion and regulatory attention typically focuses first, and often exclusively, on the processor, although evidence from outbreak investigations suggests that the field is often the source of the original contamination. Once produce is contaminated, fresh-cut processors cannot completely decontaminate the raw products with currently available processing technologies. Thus, food safety must be based on prevention programs such as HACCP (U.S. FDA, 2008).

18.4.2 FROZEN

Packaging materials for frozen fruits and vegetables must protect the product from moisture loss, light and O_2, of which the former is the most important. Freezer burn or sublimation of water vapor from the surface of frozen foods results in their becoming dehydrated with a concomitant loss in weight, and their visual appearance deteriorates. All the common polymeric films have satisfactory water vapor transmission rates at freezer temperatures.

The earliest form of packaging material for frozen fruits and vegetables was waxed cartonboard, often with a moisture-proof RCF overwrap. These were then replaced with folding cartons having a hot melt coating of PVdC copolymer and the ability for the flaps to be heat sealed. Although still used to a small extent for low production volumes, the majority of frozen fruits and vegetables today are packaged in polymeric films based on blends of polyolefins, the major component of which is LLDPE. It is also common for the film to contain a white pigment to protect the contents from light, which could oxidize the pigments. The film is usually supplied in roll form from which it is converted into a tube, then filled and sealed continuously in a FFS type of machine. Premade bags are used for low volume packaging operations.

18.4.3 Canned

The thermal processes used for canned fruits and vegetables differ markedly depending on the pH of the product: low acid products, that is, products with a pH greater than 4.5 (which includes most vegetables) require a full 12D process, typically 60–90 min at 121°C. In contrast, those products with a pH less than 4.5 need only a mild heat treatment, typically 20 min in boiling water. Some products are acidified to lower the pH below 4.5 and thus avoid the more severe heat treatment.

The majority of "canned" fruits and vegetables are packaged either in tinplate or ECCS cans or glass jars. The cans must have the correct internal enamel applied to avoid corrosion of the tinplate. It is important that all the air is removed from the product prior to packaging to minimize corrosion of the tinplate. For acid fruits such as raspberries, which contain red/blue anthocyanin pigments, the enamel coating must be particularly rigorous since the pigments act as depolarizers, accelerating the rate of corrosion. With some fruits, only the ends of the can are enameled, and for pineapple, a plain can is used so that as the tin dissolves from the tinplate, it reacts with certain constituents of the pineapple and a yellow color develops. White aluminum-pigmented epoxy resin enamels are used with fruits in some countries.

Many vegetables contain sulfur compounds which can break down during heat processing to release H_2S. This can react with the tin and iron of the metal can to form black metallic sulfides which cause an unsightly staining of the can and also of the contents. While this process is encouraged and, indeed, is essential for the production of the desired flavor and color in canned asparagus, it is avoided with other vegetables by the use of special enamels which contain zinc oxide. This reacts with the H_2S to produce barely detectable white zinc sulfide on the inner surface of the can. White aluminum oxide-pigmented enamels based on epoxy resins are also used for cans containing vegetables.

Glass containers are still used for packaging some commercially processed fruits and vegetables, generally for products at the premium end of the market. This is largely because the production rates for glass containers are much lower than those possible for metal cans. Cylindrical, widemouth glass jars are commonly used with either a twist-off or pry-off cap coated with a suitable lining material. Considerably greater operator skills are required to retort glass jars compared to metal cans, because failure to control the overpressure correctly can result in either shattered containers or the loss of pry-off caps.

Retortable pouches made from laminates of plastic film generally with an aluminum central layer can also be used for the packaging of fruits and vegetables which are preserved by the use of heat.

18.4.4 Dehydrated

The packaging of dehydrated fruits and vegetables requires the use of a package that will prevent or, at the very least, minimize the ingress of moisture and, in certain instances, O_2. For example, products that contain carotenoid pigments (e.g., carrots and apricots) can undergo oxidative deterioration, and dehydrated potatoes are liable to develop stale rancid flavors unless O_2 is excluded. Vacuum or inert gas packaging may be used if the product is particularly sensitive to oxidation, although this is rare.

Many vegetables, for example green beans, peas and cabbage, are treated with sulfur dioxide prior to drying to retard nonenzymic browning (the principal index of failure in dehydrated vegetables) and increase the retention of ascorbic acid. Sulfur dioxide also has a useful antimicrobial effect during the initial stages of drying and, by varying the form in which it is introduced (sodium sulfite or metabisulfite), it can be used to control pH, which in turn influences the color and subsequent handling and drying characteristics of the product. Concentrations of sulfur dioxide in the dried product normally range from between 200 and 500 ppm for potatoes to between 2000 and 2500 ppm for cabbage.

For the packaging of dehydrated fruits and vegetables, the material normally used consists of one or more polymeric films having the desired barrier properties. This implies that the material must be a very good barrier to water vapor and, depending on the particular product, a good barrier to O_2 and maybe SO_2 and certain volatiles. For premium products, it is common to use a laminate where the center layer is aluminum foil coated on both sides with polymeric films.

18.4.5 VEGETABLE OILS

Vegetable oils are derived from plants and chemically are composed of triglycerides and several other minor components, which may be very important for different aspects such as nutritional properties. Edible vegetable oils are vulnerable to quality deterioration and must be adequately protected by packaging throughout their commercial life. Sources of edible vegetable oils are many and varied, and their quality attributes such as nutritional properties, health benefits, lipid composition, odor and color are very important. Oils are in general microbiologically stable due to very low moisture content, but they are subject to important chemical and physical changes (Piergiovanni and Limbo, 2010).

The most important vegetable oils used mainly or exclusively for direct consumption and cooking or frying are olive, corn and peanut oils. Olive oil has a unique position among edible oils due to its delicate flavor, stability and health benefits. Extra virgin olive oil (EVOO) is the highest grade of olive oil. To be classified as EVOO, the oil must contain less than 0.8% free fatty acid (measured as oleic acid) and the peroxide value (PV) must not exceed 20 meq O_2 kg^{-1}. Among the factors that significantly influence olive oil quality are the extraction methods, packaging materials and storage conditions such as temperature, exposure to light and contact with O_2. Oxidation leading to rancidity is the most important cause of oil spoilage, and many factors influence oxidation including O_2 dissolved in the oil when packaged, O_2 in the package headspace, O_2 diffusion through the package walls, light, temperature, humidity, pro-oxidant trace metals such as copper and iron, and, obviously, the chemical composition of the oil and natural antioxidant content (Cecchi et al., 2009).

Many different kinds of packaging are used for vegetable oils: tinplate cans, glass bottles, PET, PVC or HDPE plastic bottles, and paper-based cartons are most common. The selection of the kind of package to be used is generally done on the basis of marketing and economic criteria; however, proper packaging should provide conditions to assure adequate shelf life for distribution and marketing. Even though oils are quite stable products, the physicochemical characteristics of packaging materials may significantly affect oil quality during their shelf life. Furthermore, as well as the specific properties of the materials, the packaging geometry and the techniques of filling and closing the containers may also be very important (Piergiovanni and Limbo, 2010).

While O_2 permeability is an important property only for plastic packages, light transmission is important for both glass and plastics. PET, like glass, is an effective barrier to light at wavelengths shorter than 340 nm. On the other hand, while glass containers are able to completely prevent O_2 permeation, PET is only able to slow down the O_2 exchange. The barrier properties of PET can be improved by coating with SiO_x or amorphous carbon. Alternatively, O_2 scavengers (OS) can be added to the plastic matrix.

Glass containers are widely used for bottling olive oils, not only due to marketing requirements but also because glass containers prevent O_2 permeation into the bottle, slowing down the autoxidation rate of polyunsaturated fatty acids. Clear glass, however, leads to photooxidation of olive oil and a reduction in shelf life, and therefore colored glass is preferred to prevent or at least slow down the oxidation process.

Kucuk and Caner (2005) studied sunflower oil packaged in 1 L PET and glass bottles, both with and without headspace and stored in conditions of light (intensity unspecified) and darkness for 9 months. Oil stored in glass and PET in the dark showed very little oxidation and maintained its original profile for a long period as shown in Table 18.8.

TABLE 18.8
Effect of Packaging Materials (With or Without Headspace, in Dark/Light Conditions) and Storage Time on Mean Peroxide Values (meq O_2 kg^{-1}) in Sunflower Oil

			Storage Time (Months)				
Package	**With–Without Headspace (Air)**	**Dark/Light**	**0**	**3**	**6**	**9**	**Mean**
PET	Air	Light	0.230	0.800	3.306	14.85	4.79^{c}
		Dark	0.230	0.400	0.800	1.250	0.67^{d}
	Without air	Light	0.230	0.800	3.000	13.90	4.48^{f}
		Dark	0.230	0.400	0.500	1.100	0.55^{ad}
Glass	Air	Light	0.230	0.990	4.740	10.60	4.14^{h}
		Dark	0.230	0.310	0.430	1.010	0.49^{a}
	Without air	Light	0.230	0.776	3.133	8.670	3.20^{c}
		Dark	0.230	0.300	0.530	0.770	0.44^{a}

Source: Kucuk, M. and Caner, C., *J. Food Lipids*, 12, 222, 2005.

Means with different letters are significantly different ($P < 0.01$); standard error 0.0764.

As expected, significantly higher PVs were produced in oil exposed to light than in oil stored in the dark. The authors concluded that glass provided better protection from oxidation than PET bottles, although the latter provided adequate protection, especially when stored in the dark.

In order to reduce the diffusion of O_2 into bottled oil, various solutions have been tried; the most popular involve the use of OS which remove O_2 dissolved in the oil and provide a barrier to O_2 diffusion from the atmosphere. Sacchi et al. (2008) studied the oxidation of EVOO and sunflower oil (SO) stored in PET bottles with two different OS concentrations (1% and 5%). The bottles were stored for 6 months at 25°C under a constant illumination of 400 lux. During the first 3 months of storage, the effect of the scavengers was evident: oils bottled in PET loaded with 5% of OS showed a dissolved O_2 (DO) content lower than oils bottled in PET with 1% OS and in standard PET. Between 3 and 6 months, the level of DO remained almost constant in all packages, indicating that the O_2 consumed during storage was nearly limited to the initial content in the oil. However, the different initial levels of DO raise questions about the validity of their conclusions.

Cecchi et al. (2010) compared 300 mL PET bottles with and without OS on the quality of EVOO over 13 months. The bottles had 2 mL headspace and were stored in the dark or diffuse light at 20°C–22°C. The fatty acid concentration remained constant at 0.3% oleic acid in all bottles over 13 months. For all treatments, peroxides first decreased and subsequently increased over time but always remained below the threshold limit (20 meq O_2 kg^{-1}). This indicates that in the first stage of oxidation, the rate at which hydroperoxides are consumed is higher than the rate at which they are produced through the oxidation of unsaturated fatty acids, leading to a decrease in PV. This highlights a possible role of the PET material in consuming the peroxides. Moreover, PVs of samples stored in the dark were higher than those stored in diffuse light, probably because light increases the rate at which hydroperoxides break down.

Pristouri et al. (2010) studied the effect of packaging parameters (transmission to light and O_2, headspace volume) and storage temperature (13°C, 22°C and 35°C) on quality characteristics of EVOO as a function of storage time (0–12 months). Packaging materials tested included clear glass, clear PET, clear PET + UV blocker, clear PET covered with aluminum foil and clear PP bottles. Changes in the acidity and PV of EVOO stored in the dark at 22°C as a function of packaging material and storage time are summarized in Table 18.9. The best packaging material for EVOO was glass followed by PET; PP proved to be unsuitable for such an application.

TABLE 18.9
Changes in Acidity and PV of Olive Oil Stored in the Dark at 22°C as a Function of Packaging Material and Storage Time

	Acidity (% Oleic Acid)			Peroxide Value (meq O_2 kg^{-1})		
Time (Month)	Glass	PET	PP	Glass	PET	PP
0	0.63	0.63	0.63	12.92	12.92	12.92
3	0.68	0.68	0.70	13.07	14.24	15.93
6	0.68	0.71	0.74	16.57	17.95	19.00
9	0.70	0.79	0.79	17.53	19.75	21.57
12	0.75	0.79	0.83	18.86	20.61	22.54
Limits	≤0.8%			≤20		

Source: Pristouri, G. et al., *Food Control*, 21, 412, 2010.

Exposure of EVOO to light, high storage temperatures (35°C) and large headspace volumes caused substantial deterioration in product quality parameters. The most pronounced effect was that of temperature and light, while the smallest effect was that of headspace volume and packaging material permeability to O_2. Olive oil color was not substantially affected by storage conditions with the exception of storage of olive oil at 35°C exposed to light for 12 months. Shelf life of EVOO was 6 months packaged in clear glass in the dark at temperatures up to 22°C; 3 months in clear PET in the dark at 22°C and less than 3 months in clear PP in the dark at 22°C. When exposed to light, shelf life of EVOO was 9 months when packaged in PET + aluminum foil; 3 months in PET + UV blocker and less than 3 months in clear PET at 22°C. Product shelf life was less than 3 months at 35°C. Finally, O_2 in the headspace resulted in deterioration of product quality. The relative contribution of parameters studied to the retention of EVOO quality was temperature ≈ light > container headspace > packaging material O_2 permeability.

Recently, Samaniego-Sánchez et al. (2012) reported changes in the chemical composition and sensory characteristics of EVOO resulting from storage for up to 9 months in the dark at 4°C and 20°C in glass and PET bottles and LDPE-coated paperboard/alufoil laminate cartons. All container types had the same surface area and no headspace. Losses in both qualitative properties and minor components, as well as antioxidant capacity and sensory features, were detected in all oil samples, especially for oils stored in PET and glass, but less so for those stored in cartons. As far as sensory characteristics were concerned, the EVOOs packed in PET and glass containers exceeded the European limits after 3 month of storage, while the samples stored in cartons maintained acceptable sensory characteristics for at least 9 months.

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