

Modified Atmosphere Packaging

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Introduction

Modified-atmosphere packaging (MAP) of fresh fruits and vegetables refers to the technique of sealing actively respiring produce in polymeric film packages to modify the O₂ and CO₂ levels within the package atmosphere. It is often desirable to generate an atmosphere low in O₂ and/or high in CO₂ to influence the metabolism of the product being packaged or the activity of decay-causing organisms to increase storability and/or shelf-life. For some products, modifying both O₂ and CO₂ may be desirable; indeed, altering the O₂ level automatically alters CO₂ level. In addition to atmosphere modification, MAP vastly improves moisture retention, which can have a greater influence on preserving quality than O₂ and CO₂ levels. Furthermore, packaging isolates the product from the external environment and helps to ensure conditions that, if not sterile, at least reduce exposure to pathogens and contaminants.

MAP was first evaluated in the mid to late 1940s for its ability to reduce O₂ levels sufficiently to slow the ripening of apple fruit. The primary limitation of MAP application in the early studies was technical in nature—specifically, the lack of consistent control of O₂ levels in the package. Since then, the types and properties of polymers have increased to provide a wider range of gas permeability, tensile strength, flexibility, printability, and clarity. As a result, successful modified atmosphere (MA) packaging systems have been developed for a number of commodities.

It is important to recognize that while atmosphere modification can improve the storability of some fruits and vegetables, it has the potential to induce undesirable effects. Fermentation and off flavors may develop if decreased O₂ levels cannot sustain aerobic respiration (Kays 1997). Similarly, injury will occur if CO₂ exceeds tolerable levels. Ranges of nondamaging O₂ and CO₂ levels have been published for a number of fruits and vegetables (Kader 1997a, Kupferman 1997, Richardson and Kupferman 1997, Saltveit 1997, Beaudry 1999, 2000), minimally processed products (Gorny 1997), and flowers and ornamentals (Reid 1997). Horticultural crops differ in their tolerance for O₂ (table 1) and CO₂ (table 2). The range of O₂ and CO₂ levels for fruits (figure 1) and vegetables (figure 2) can overlap or be distinct.

Table 1. O₂ limits below which injury can occur for selected horticultural crops held at typical storage temperatures

O ₂	Commodities
%	
<0.5	Chopped greenleaf*, redleaf*, romaine* and iceberg lettuce*; spinach; sliced pear; broccoli*; mushroom
1.0	Broccoli florets, chopped butterhead lettuce, sliced apple, brussels sprouts, cantaloupe, cucumber, crisphead lettuce, onion bulbs, apricot, avocado, banana*, cherimoya, atemoya, sweet cherry, cranberry, grape, kiwifruit*, litchi, nectarine, peach, plum, rambutan, sweetsop
1.5	Most apples*, most pears*
2.0	Shredded and cut carrots, artichoke, cabbage*, cauliflower, celery, bell and chili peppers, sweet corn, tomato, blackberry, durian, fig, mango, olive, papaya, pineapple, pomegranate, raspberry, strawberry
2.5	Shredded cabbage, blueberry
3.0	Cubed or sliced cantaloupe, low-permeability apples* and pears*, grapefruit, persimmon
4.0	Sliced mushrooms
5.0	Green snap beans, lemon, lime, orange
10.0	Asparagus
14.0	Orange sections

Source: Gorny 1997, Kader 1997a, Kupferman 1997, Richardson and Kupferman 1997, Saltveit 1997, and Beaudry 2000

* Considered to have very good to excellent potential to respond to low O₂.

Table 2. CO₂ partial pressures above which injury will occur for selected horticultural crops

CO ₂	Commodities
kPa	
2	Lettuce (crisphead), pear
3	Artichoke, tomato
5	Apple (most cultivars), apricot, cauliflower, cucumber, grape, nashi, olive, orange, peach (clingstone), potato, pepper (bell)
7	Banana, bean (green snap), kiwifruit
8	Papaya
10	Asparagus, brussels sprouts, cabbage, celery, grapefruit, lemon, lime, mango, nectarine, peach (freestone), persimmon, pineapple, sweet corn
15	Avocado, broccoli, lychee, plum, pomegranate, sweetsop
20	Cantaloupe (muskmelon), durian, mushroom, rambutan
25	Blackberry, blueberry, fig, raspberry, strawberry
30	Cherimoya

Source: modified from Herner 1987, Kader 1997a, and Saltveit 1997

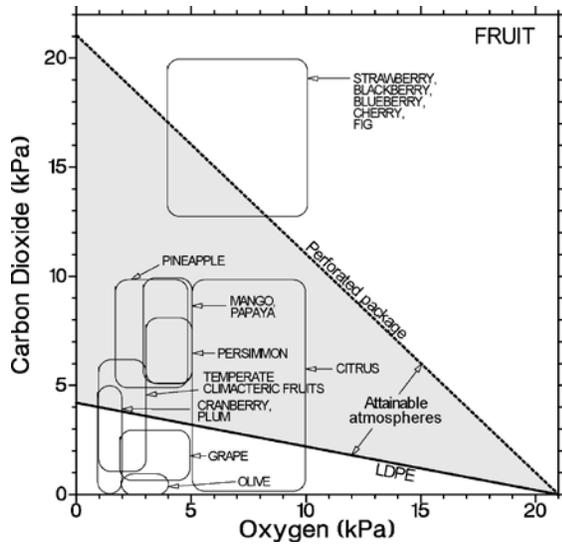


Figure 1. Recommended O₂ and CO₂ combinations for the storage of fruit. The chart depicts atmospheres theoretically attainable by MAP by film permeation alone (low-density polyethylene, LDPE, lower boundary) and via perforations alone (upper, dashed line) or their combination (shaded area). Data are adapted from Kader (1997) and reprinted with permission from Beaudry (1999). Copyright 1999 by Elsevier Science.

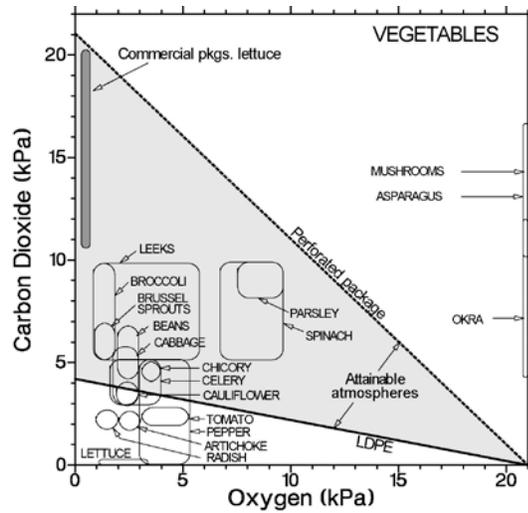


Figure 2. Recommended O₂ and CO₂ combinations for the storage of vegetables. The chart depicts atmospheres theoretically attainable by MAP using low-density polyethylene (LDPE, lower boundary) and perforated packages (upper, dashed line); redrawn from Mannapperuma et al. (1989). The shaded area represents atmospheres observed in commercial MA packages of mixed lettuce-based salads (Cameron et al. 1995). Reprinted with permission from Beaudry (1999). Copyright 1999 by Elsevier Science.

The composition of the atmosphere within a package results from the interaction of a number of factors that include the permeability characteristics of the package, the respiratory behavior of the plant material, and the environment. The films making up the package are selected to have specific permeability characteristics, and changes in these characteristics over time, temperature, and humidity follow known physical laws. The environment can be controlled to provide specific conditions. In contrast to these known and controllable factors are the often unknown and uncontrollable responses of the plant material. Plant species and cultivar, cultural practices, stage of development, manner of harvest, tissue type, and postharvest handling—all of these factors contribute and influence the response of the material to the generated atmosphere. The scope of plant responses can be further modified by initial gas flush of the package before sealing and inclusion of chemical treatments to slow unwanted processes or reduce decay. Each of these components of the packaging process can be examined separately to better illustrate how each contributes to packaging strategies.

Package Parameters

Atmosphere modification in MAP requires actively respiring plant tissue and a barrier through which gas exchange is restricted. The reduced O₂ and increased CO₂ resulting from tissue respiration create gradients across the film barrier that provide the driving force for gas movement into and out of the package. The levels of O₂ and CO₂ within a package depend on the interaction between commodity respiration and the permeability properties of the packaging film or microperforations (Beaudry et al. 1992, Kader et al. 1997a).

There are two strategies for creating film. The first employs continuous films that control movement of O₂ and CO₂ into or out of the package. The second uses perforated films with small holes, or microperforations, as the primary route of gas exchange.

Continuous Films: The movement of O₂ and CO₂ is usually directly proportional to the difference in gas concentration across the film. Steady-state (constant) O₂ and CO₂ levels are achieved in the package when the O₂ uptake and CO₂ production by the product are equal to that permeating through the film, a situation that exists only when the respiratory rate is constant.

Perforated Films: The rate of gas movement through a perforated film is the sum of gas diffusion through the perforation and gas permeation through the polymeric film. Generally, total gas flow through the perforations is much greater than gas movement through the film. Gas transmission through microperforations has been modeled (Fishman et al. 1996). The rate of gas exchange through perforations in a film is so much greater than through continuous films that a 1-mm perforation in a 0.0025 mm (1 mil) thick low-density polyethylene (LDPE) film has nearly the same gas flux as a half a square meter area of the film. As might be surmised, perforated packages are more suitable for produce having a high O₂ demand.

Gas Exchange Properties of Continuous and Perforated Films

The relative permeability of the package to O₂ and CO₂ differs substantially between continuous and perforated films and results in considerable differences in gas exchange behavior. In packages composed of continuous films, the permeability of the package to CO₂ is usually 2 to 8 times that of O₂ permeability. If the rate of O₂ uptake by the product is roughly the same as its production of CO₂ (the normal case unless fermentation is taking place), the CO₂ gradient will be much lower than the

O₂ gradient. For example, low-density polyethylene (LDPE) has permeability to CO₂ that is four times that of O₂. In a LDPE package having a 10% O₂ steady-state atmosphere, the CO₂ level could be calculated as $(21 - 10\%)/4$, or 2.75% CO₂. (Air contains 78% N₂, 21% O₂, and 0.03% CO₂.) For perforated films, the permeability to CO₂ is only 0.77 times that of O₂. As a result, in a package relying on perforations for gas exchange, CO₂ levels climb to roughly the same extent that O₂ levels decline (that is, the gradients are nearly equal) such that the sum of O₂ and CO₂ partial pressures is usually in the range of 18 to 20%. For any given O₂ level, therefore, the perforated package will have a considerably higher level of CO₂ compared with the continuous film package. To extend the example above, if a package were designed to have a 10% O₂ steady-state atmosphere using perforations as the route of gas exchange, the CO₂ level would be $0.77 \times (21 - 10\%)$, or 8.8%, which is about 3-fold greater than in the continuous film package. The relative elevation of CO₂ in perforated film packages may be critically important in package design, if CO₂ is needed to help control decay or degreening.

MAP relying on a combination of perforation and permeation has features of both systems, with attainable combinations of O₂ and CO₂ being between those of packages relying on permeation and those relying on perforations (Mannapperuma et al. 1989, Beaudry 1999) (figures 1 and 2). The temperature sensitivity for permeation, and the permeability of O₂ and CO₂, is somewhere between those for perforated packages and continuous film packages.

Temperature is extremely important in package design, and continuous and perforated films differ in their response to temperature changes. The O₂ and CO₂ permeability of continuous films increases with temperature, while the diffusion of gases through perforations is extremely insensitive to temperature changes. For instance, O₂ permeation through LDPE can increase 200% from 0 to 15 °C, but the exchange of O₂ through perforations will increase only 11% across this temperature range.

Depending on the rates of respiration and transmission through the package, atmosphere modification can be achieved rapidly or relatively slowly. At low temperatures, atmosphere modification can take several days, such that some package systems would not achieve steady-state conditions before the end of their shelf-life. In many cases, purging the package atmosphere with CO₂, N₂, or a combination of gases is often desirable during filling and sealing to rapidly obtain the maximum benefits of MAP.

Respiratory Parameters

The maximal rate of respiration for most fruit and vegetable products undergoes a 4- to 6-fold increase from 0 to 15 °C (Beaudry et al. 1992, Cameron et al. 1994,1995, Lakakul et al. 1999). This means that product respiration increases at 2 or 3 times the rate of LDPE permeability and 30 times the rate of perforation permeability with increasing temperature. When respiratory demand for O₂ increases faster than O₂ permeation as temperature increases, O₂ levels decline and may pose a risk to product quality, limiting the usefulness of MAP in some situations.

Safe levels of O₂ and CO₂ are important for package design. A lower O₂ limit has been associated with onset of fermentation and accumulation of ethanol and acetaldehyde (Beaudry et al. 1992). Fermentation is linked to the development of off flavors and tissue damage. Effect of temperature on lower O₂ limit has been measured for a number of commodities including whole apple, apple slices, blueberry, and raspberry. In each case, lower O₂ limit increased with temperature. Lower O₂ limits vary from 0.15 to 5% (table 1) and are influenced by temperature, commodity, and cultivar (Beaudry and Gran 1993).

Integrating Package, Product, and Environment

Mathematical models can integrate the film permeability to O₂, to CO₂, and to H₂O and the respiratory response of the commodity to O₂ (and in some cases to CO₂), along with its lower O₂ limit and upper CO₂ limit (Beaudry et al. 1992, Cameron et al. 1994, Fishman et al. 1996, Hertog et al. 1998, Lakakul et al. 1999). These models enable the reasonably accurate prediction of package performance; that is, O₂-, CO₂-, and H₂O-content in the package headspace under a variety of environmental conditions prior to construction of the package. Additionally, they permit the identification of limiting features of the film, package design, and product and environment conditions. Models typically include temperature dependency but can also be developed to predict effects of package volume, resistance to heat flow, and developmental changes in product physiology on headspace gases.

Predicting and Controlling O₂ and CO₂ Content

A model can be developed to predict the steady-state concentration of O₂ in the package headspace. Steady-state models incorporating temperature effects on respiration and permeability have been published for many commodities. In addition, more complex dynamic models have been developed to account for temporal changes in package volume, product respiration, and the humidity and temperature of the environment (Fishman et al. 1996, Hertog et al. 1998).

Package performance can be depicted in a number of ways. Perhaps the most instructive format is describing the effects of temperature on package O₂ levels. For example, a package was designed to produce low O₂ and high CO₂ levels for 100 g of apple slices at 0 °C (Lakakul et al. 1999). The practical O₂ limit was set 3-fold higher than the fermentation threshold to prevent variation in respiration and permeability from causing a reduction in package O₂ below the lower limit. If the package relied on perforations for gas exchange, it would undergo a rapid decline in O₂ by the time the package reached 6 °C (43 °F). Films with higher temperature sensitivity would be less prone to risk fermentation. In this example, packages were designed to maintain aerobic O₂ levels at 15 °C, the highest temperature to which they would be exposed. The performance of the packages can then be predicted at lower temperatures likely to be encountered during storage. A package O₂ model can also be used to predict very specific package criteria. For instance, the 100 g of apple slices described above were in a container with a film area of 120 cm². Film thickness and composition with different permeability characteristics could be selected to protect against fermentation.

A package model can also be used to clarify the nature of the mismatch between the temperature sensitivity of O₂ uptake and O₂ flux through the film and denote methods to ameliorate this problem. One method would be to choose a film with permeability changes for O₂ similar to that of the respiration of the product, so if temperature increases, respiration and permeability of the film increase an equivalent amount.

Another solution to the MAP temperature problem is to develop a package system that senses either the environment or the physiological status of the enclosed product and responds by increasing the permeability to O₂ (Cameron et al. 1993). Such “sense-and-respond” packaging is technically difficult to develop, and progress has only been conceptual at this time (Smyth et al. 1999). A third approach is to design packages to function at the highest temperatures typically encountered in the distribution

and retail cool chain and, as far as possible, maintain control over the temperature of the packaged product, thereby adapting to the limitations imposed by the film. Most companies using MAP have adopted this simple solution. Generally, the lowest temperature feasible is maintained, since temperature has a much more significant influence on preserving quality than the application of low O₂ (Kays 1997).

Variation in the respiration rate of the product and the variation in film or pore permeability can influence package design. Variation in product respiration and package permeability has been measured for broccoli, and the effect on package O₂ modeled (Cameron et al. 1993). Cameron et al. (1993) concluded that there is an estimable risk of the package O₂ falling sufficiently low to promote fermentation in any product. Packages should be designed to generate O₂ levels well above the lower limit to ensure aerobic conditions.

Products such as broccoli, mushrooms, and leeks have very high rates of respiration, and most continuous films do not have the capacity to provide enough O₂ to avoid fermentation. Accordingly, there is commercial interest in developing films with high gas transmission rates. Films that have improved rates of gas transmission by virtue of their polymeric nature are often blends of two or three different polymers, with each polymer performing a specific function such as strength, transparency, and improved gas transmission. Similarly, films can be laminated to achieve needed properties.

The plastic polymer can also be mixed with an inert inorganic material such as CaCO₃ and SiO₂ to generate microporous films. Gas permeabilities can be manipulated by adjusting the filler content, particle size of the filler, and degree of stretching. The average pore size ranges from 0.14 to 1.4 μm in diameter (Mizutani, 1989). Films using microperforations can attain very high gas transmission rates. The diameter of microperforation generally ranges from 40 to 200 μm; and, by altering the size and thickness of microperforations, gas permeability through a package can be altered to meet well-defined product requirements. Microperforated films have also been used to extend storage of strawberries and nectarines (Meyers 1985) and apple (Watkins et al. 1988).

Water Vapor

Plant tissues tend to lose moisture when RH is below 99 to 99.5%. Generally, water loss results in visible wilting or wrinkling of the surface of most commodities when it exceeds 4 to 6% of total fresh weight (Kays 1997). Fortunately, most MAP films are relatively impermeable to water. The RH is very near saturation in most continuous or perforated film packages. A saturated atmosphere at 20 °C (68 °F) has only 2.1% H₂O, and most external environments are at 30 to 60% RH, yielding a water vapor gradient of about 1%. The O₂ gradient can be several-fold higher. Because of the small driving force and the rapid rate of release of water vapor from the product, perforations have a much greater effect on the O₂ level than on RH. Fishman et al. (1996) calculated that perforating a continuous film increased O₂ flow 40-fold more than it increased H₂O flow. Only four perforations were required to achieve near-ambient O₂ levels, while 40 perforations only reduced RH to 95%

Condensation on the inner surface of the film is a common problem with MAP. A drop of only 0.2 °C in the film temperature can result in condensation in a package with an internal RH of 99% at 10 °C. Cold-storage rooms have temperature swings of several degrees, so condensation is possible in almost any MAP. Fortunately, there are film surface treatments that result in droplet dispersion, so the condensing water forms a thin, uniform layer that is virtually invisible. Condensation could also be

reduced in MAPs for a few commodities, such as tomato, that tolerate low humidity by including materials in the package that reduce RH. Salts enclosed in permeable sachets can reduce humidity in MAPs of tomato fruit (Shirazi and Cameron 1992). The possibility of using films with very high water permeability has been examined using mathematical models (Cameron et al. 1995). However, since the external humidity would be critical in maintaining the proper package RH, this approach would encounter difficulty in maintaining a specific humidity level in shipping and storage environments.

Temperature Management

Product temperature affects storability more than any other factor. Precooling and temperature maintenance during handling and shipping are critical in preserving quality. Temperature also significantly affects film permeability and thereby the O₂ and CO₂ content of the package. The elevated rate of respiration at high temperature could be used to rapidly establish the desired package atmosphere, but this would only be useful in the few situations in which it would be more important to rapidly establish the atmosphere than to slow physiological processes—for example, to reduce cut-surface browning. Cameron et al. (1995) calculated that, at 25 °C (77 °F), a package of blueberry fruit could attain a steady-state atmosphere in less than 2 days, whereas it required approximately 20 days at 0 °C (32 °F).

The temperature of the produce in the package is managed by circulating cool air around the outside of the package. The film and the headspace atmosphere are barriers to heat movement, prevent rapid cooling, and reduce the effectiveness of refrigeration. A “safe radius” for the distance from the center of the package to the circulated air can be calculated based on the heat of respiration and the rate at which heat can be removed by the cooler air (Sharp et al. 1993). For instance, the center of a package of broccoli must have a radius of less than 14 cm to keep it within 1 °C of the refrigerated air. Slower-respiring pear would function as well with a larger package having an effective radius of 50 cm.

Plant Responses to MAP

Some of the most important factors that affect shelf-life of fresh horticultural products are ripening and senescence, decay, and cut-surface browning. The effect of MA on these factors has been well characterized. The application of MA to affect these limiting factors can be restricted for some crops by adverse or nonbeneficial physiological responses; for example, induction of fermentation. Fresh product quality can be maximized more effectively by good temperature management than by atmosphere modification.

Ripening and Senescence

Low O₂ and elevated CO₂ can significantly reduce the rates of ripening and senescence primarily by reducing the synthesis and perception of ethylene (Burg and Burg 1967, Abeles et al. 1992). Changes in respiration and starch, sugars, chlorophyll, and cell wall constituents during ripening and/or senescence can be reduced and, in some cases, nearly arrested by eliminating ethylene action through the use of low O₂/high CO₂ atmospheres.

Chlorophyll loss, a desirable trait for many climacteric fruits, results in quality loss for many vegetables. Chlorophyll degradation during the senescence of green vegetables can be inhibited by low

O₂ and elevated CO₂, a response that in some cases is partly mediated by ethylene, as with broccoli (Ku and Wills 1999).

While low O₂ and elevated CO₂ atmospheres are commonly used to minimize ethylene-dependent responses attendant to ripening in CA rooms, this goal may not be fully compatible with MAP. The problem with the incorporation of MAP for ripening control is not one of efficacy, but rather one of logistics. Modified atmospheres are most effective at reducing ripening prior to the onset of ripening, rather than at a later stage. However, packaged products are usually intended for immediate consumption and an unripe product is not immediately edible or is of lesser quality than the ripe product. Thus, the advantage of improved shelf-life by retarding ripening runs counter to the needs of the consumer when retail MAP systems are used. Nevertheless, MAP can reduce the rate of ripening of some commodities such as tomato even during its later stages (Yang and Chinnan 1988). More potential for using MAP to control ripening may exist at the packinghouse or distributor level, as in the case of overseas shipment of apples (Watkins et al. 1998), rather than at the retail level.

Decay

Decay control is a particularly important problem for many crops. Levels of >10% CO₂ effectively slow or stop the growth of numerous decay organisms (Brown 1922). Low O₂ has a very limited effect on decay organism activity or survival at levels above the fermentation threshold of most commodities. While not all horticultural commodities can withstand CO₂ levels sufficient to inhibit fungal activity, a number of highly perishable commodities are not adversely affected (table 2). Notable among these are strawberry, blueberry, blackberry, raspberry, and cherry, which can be stored successfully under a CO₂ atmosphere of 10 to 20%.

Packaging strategies to enhance CO₂ include initial purging with high levels of CO₂. This strategy relies on continued respiration to replace CO₂ lost from the package and is in commercial use for many berry crops. The choice of film type markedly alters the CO₂ content of a package. In particular, perforated and continuous films differ in their discrimination between O₂ and CO₂. Perforated films will generate a higher partial pressure of CO₂ for a given concentration of O₂ in the package. Perforated packages can accumulate CO₂ to levels within the fungistatic range. For example, a perforated package that generates 1% O₂ could accumulate a 15% CO₂ atmosphere.

While high RH reduces water loss, it also aggravates decay development. Strategies to reduce humidity in packages using salt sachets for the purpose of limiting decay have been explored (Shirazi and Cameron 1992). A number of effective chemical additives can be used at various points during processing and packaging to reduce decay.

Cut-Surface Browning

Mostly, low-O₂ MAP is used to reduce the browning of cut surfaces on lightly processed products such as lettuce and salad mixes. Atmosphere modification is often used in conjunction with processing aids to retard brown color development. Smyth et al. (1998) demonstrated that O₂ levels below 2% but above the fermentation threshold of about 0.5% reduced the rate of browning in lettuce. The partial pressure of O₂ in commercial packages of lettuce and salad products is often below the fermentation threshold (Cameron et al. 1995, Peiser et al. 1997). However, the fermentation of lettuce, if not severe, results in very few off flavors (Smyth et al. 1998).

Negative Responses

Respiration is reduced as O₂ becomes limiting, but there is usually a limit to which O₂ can be reduced. The lower O₂ limit is frequently considered to be the level of O₂ that induces fermentation. This fermentation threshold is not always the lower O₂ limit in commercial practice, however, because lower O₂ levels may confer benefits that outweigh the loss in flavor or other quality parameters. Ethanol, acetaldehyde, ethyl acetate, and lactate are products of fermentation that can contribute to the development of off flavors as well as physical injury (Kays 1997, Mattheis and Fellman 2000).

Production of compounds that contribute to the characteristic aromas of many fruit, such as apples, bananas, pears, peaches, and strawberries, can be adversely affected by low O₂ and elevated CO₂ (Song et al. 1998, Mattheis and Fellman 2000). Synthesis of aroma compounds are generally suppressed by high CO₂ and low O₂, in part by their action on ethylene perception but also via action of O₂ on oxidative processes, including respiration required for substrate production. Most products that suffered moderate suppression of aroma volatile production due to low-O₂ storage atmospheres will eventually develop characteristic flavors. However, low-O₂ MAP may suppress aroma production so consumers perceive reduced quality upon opening the container.

Conclusion

A number of critical points need to be considered in package design and application:

- Not all plant materials benefit from MAP. Those that do may differ in their responses to the atmospheres generated.
- Consideration should be given to the factor most limiting to the delivery of a product to the consumer, and the packaging strategy should be developed accordingly.
- Reduction of water loss by packaging has a marked influence on storability. Elevated humidity prevents desiccation but can also enhance decay.
- Temperature control is of critical importance and, by itself, has a greater impact than atmosphere modification for most products. Temperature should be near the storage/shipping temperature as soon as possible after packaging except in those cases for which a slightly elevated temperature is needed to assist in rapid atmosphere generation.
- Heat transmission from product through the package, carton, and pallet stack needs to be considered in the development of handling procedures.
- If a package is designed to produce low-O₂ or high-CO₂ levels at low temperatures, temperatures more than a few degrees above the target temperature should be avoided, or low-O₂ injury may result.
- Package modeling can improve understanding of how package, plant, and environmental factors interact and can be useful in package design.

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