Modified Atmosphere Packaging of Fresh Produce

Many factors must be considered in creating gaseous microenvironments for packaged produce to maintain the quality of fresh fruits and vegetables

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THE QUALITY of fresh produce depends primarily upon the selection and careful handling of good product. Such measures as harvesting at optimal maturity, minimizing injury due to handling, reducing microbial infection through proper sanitation, and maintaining optimum temperature and humidity are important in maintaining postharvest quality. Once these primary requirements have been met, further maintenance of produce quality can be achieved through modification of the atmosphere surrounding the product (Fig. 1). Modified atmosphere packaging provides such a means.

This article details the effects and development of modified atmospheres in the packaging of fresh produce. It also describes films for modified atmosphere packaging and compares several mathematical models of atmospheric modification within packages.

Definition and Effects of Modified Atmosphere Packaging

Historically, atmospheres surrounding produce have been altered in controlled atmosphere (CA) storage facilities where the levels of gases are continually monitored and adjusted to maintain the optimal concentrations. This high degree of atmospheric regulation associated with CA is capital intensive and expensive to operate and thus is more appropriate for commodities that are amenable to long-term storage such as apple, cabbage, kiwifruit, and pear (Kader et al., 1988). Modified atmosphere (MA) storage implies a lower degree of control of gas concentrations. Typically, initial atmospheric conditions are established for a transient period, and the interplay of the commodities' physiology and the physical environment maintain those conditions within broad limits.

Advances in the design and manufacture of polymeric films with a wide range of gas permeability characteristics have stimulated interest in creating and maintaining modified atmospheres within flexible film packages. The availability of absorbers and adsorbers of O₂, CO₂, ethylene (C₂H₄), and water provides additional tools for maintaining a desired atmosphere within a package. Such modified atmosphere packaging (MAP) could be applied to shipping containers, retail packages containing several intact or sliced commodity units, or retail packages for individual units of the commodity (Kader et al., 1988).

The benefits and hazards of CA and MA have been reviewed (Brecht, 1980; Dewey, 1983; Dilley, 1983; Isenberg, 1979; Kader, 1980; Kader, 1986; Kader et al., 1988; Lipton, 1975; Marcellin, 1977; Smock, 1979; and Wolfe, 1980). Reduced O₂ or elevated CO₂ can delay fruit ripening, reduce respiration and ethylene production rates, reduce ethylene sensitivity to delay ripening, retard softening, and slow down various compositional changes associated with ripening (Kader, 1986). The effects of reduced O₂ and elevated CO₂ on respiration and fruit ripening are additive and can be greater than the effects of either alone (Kader et al., 1988, and Fig. 2). However, exposure of fresh produce to levels above their CO₂ tolerance limit may cause physiological damage, and exposure to levels below their O₂ tolerance limit may increase anaerobic respiration and the development of off flavors due to accumulation of ethanol and acetaldehyde. Low O₂ and/or high CO₂ can reduce the incidence of some physiological disorders induced by C₂H₄, such as apple and pear scald and russet spotting on lettuce. Chilling injury of some commodities (e.g., avocado, citrus, okra, and peppers) may be reduced by modified atmospheres (Kawada, 1982; Risse et al., 1987; Scott and Chaplin, 1978). Other physiological disorders, such as brown stain of lettuce, internal Browning and surface pitting of pome fruits, and blackheart of potato, may be induced by inappropriate modified atmospheres (Kader et al., 1988).

In reviewing the effects of MA on pathogens of fruits and vegetables, El-Goorani and Sommer (1981) noted that delaying the senescence of fruits and vegetables—whether by MA or other means—reduces their susceptibility to pathogens. Conversely, inappropriate MA can prevent wound healing, hasten senescence, or induce physiological breakdown, making fruits and vegetables more susceptible to postharvest pathogens. Oxygen levels below 1% or CO₂ levels above 10% are needed to significantly suppress fungal growth (El-Goorani and Sommer, 1981). Carbon dioxide levels above 10% can be used for control of pathogens only with commodities that will tolerate such levels. Carbon monoxide (5–10%) combined with low O₂ (<5%) is an effective fungistat, but it is very toxic to humans and must be used with extreme care (El-Goorani and Sommer, 1981).

MAP can produce all the positive and negative effects of any modified atmosphere. It is also important to recognize that packaging has many effects on fresh fruits and vegetables, independent of the creation of...
MA. Packages are barriers to movement of water vapor and can aid in the maintenance of high relative humidity (RH) and turgor of fruits and vegetables. Maintenance of very high RH can encourage moisture condensation on the commodity, creating conditions favorable for pathogen growth. In the event of pathogen growth, individually wrapped fruits or vegetables will not contaminate other wrapped units. This restriction of the spread of disease has been mentioned as one of the principal benefits of individually shrink-wrapping citrus fruits (Ben-Yehoshua, 1985). The film can also be impregnated with fungicides or ethylene absorbers (Kader et al., 1988). Film packages can serve to protect the commodity from surface abrasions and, for some commodities such as Belgian endive and potato, from the deleterious effects of light.

Factors Affecting Modified Atmosphere Packages

The conditions created and maintained within a package are the net result of the interplay among several factors, both commodity-generated and environmental.

• Commodity Factors are discussed below.

  1. Resistance to Diffusion of O₂, CO₂, C₂H₄, and H₂O. Most fruits and vegetables are tolerant of O₂ levels down to 1–5% and CO₂ levels up to 5–10% (Kader, 1980). However, plant enzymes involved in O₂ utilization can function in an environment of less than 1% O₂ (Burton, 1978). The difference between external O₂ (or external CO₂) concentration and the amount of O₂ (or CO₂) available within the cell is determined
largely by the resistance of the plant organ to gas diffusion. Resistance to gas diffusion varies among different plants, plant cultivars, plant organs, and stage of maturity, but appears to be little affected by temperature (Cameron and Reid, 1982). Anatomical differences responsible for differing diffusion resistance, rather than biochemical differences among different fresh fruits and vegetables, may be largely responsible for differences in tolerance to low O₂ and high CO₂ in MA (Burton, 1974).

2. Respiration. Respiration in plants is the oxidative breakdown of starch, sugars, and organic acids to simpler molecules including CO₂ and H₂O, with a concurrent production of energy. Some of this energy is realized as heat and some as metabolic energy. One of the primary effects of MA is a lower rate of respiration, which reduces the rate of substrate depletion, CO₂ production, O₂ consumption and release of heat. The result is slowed metabolism and potentially longer storage life. Some of the biochemical and physiological effects of MA on fruits and vegetables have been summarized (Kader, 1986). The rate of respiration and the metabolic pathway of respiration are subject to both internal and external influences. Respiration rate changes as a commodity goes through its natural process of ripening, maturity, and senescence. Certain fruits (e.g., apple, kiwifruit, pear, tomato) experience a marked and transient increase in respiration during their ripening, known as the climacteric, that is associated with increased production of ethylene. The ratio of CO₂ produced to O₂ consumed, known as the respiratory quotient (RQ), is normally assumed to be one but can range from 0.7 to 1.3 (Forcier et al., 1987) depending on the metabolic substrate being utilized. There have been some suggestions that MA conditions can alter the RQ, which in turn will affect the atmosphere created by the respiration of the commodity within the package (Kader et al., 1988; Tomkins, 1965). The rate of respiration is sensitive to changes in O₂ concentration below about 8% and CO₂ above about 1%. However, if O₂ is reduced or CO₂ elevated beyond the levels of tolerance of the commodity, respiration associated with anaerobic respiration or CO₂ damage will increase (Fig. 2).

3. Ethylene Production and Sensitivity. Exposure of climacteric fruits to ethylene advances the onset of an irreversible rise in respiration rate and rapid ripening. A reduction in ethylene production and sensitivity associated with MA can delay the onset of the climacteric and prolong the storage life of these fruits. Even nonclimacteric fruits and vegetables can benefit from reduced ethylene sensitivity and lower respiration rate attributed to MA. Ethylene production is reduced by either low O₂, high CO₂, or both, and the effects are additive (Fig. 3).

4. Optimum Temperature. Metabolic processes, including respiration and ripening rate, are sensitive to temperature. Biological reactions generally increase two- to three-fold for every 10°C rise in temperature. Generally, fruits and vegetables will last longer at lower temperatures; however, every commodity has a lower temperature limit. Below this limit, chilling damage can occur, increasing respiration rate, hastening senescence, and lowering the value of the commodity. The optimum temperature is the one that delays senescence and maintains quality the longest without causing chilling, freezing, or other injury. Many tropical fruits (e.g., avocados, mangoes, papayas) are very sensitive to low temperature injury and should not be stored below about 13°C. Nonchilling-sensitive commodities (e.g., apples, broccoli, pears) can be stored near 0°C without ill effects.

The optimum temperature may vary, depending upon other conditions. For example, reduced O₂ or elevated CO₂ can overcome the impact of low temperature injury on the ripening process. Reduced chilling injury has been associated with elevated CO₂ in some commodities (Lyons and Breidenbach, 1987). Proper temperature management of fresh produce is perhaps the single most important part of good postharvest handling and, although the limits of temperature tolerance may be expanded slightly by MAP, the importance of maintaining optimal temperature throughout the marketing chain cannot be overemphasized.

5. Optimum Relative Humidity. Low relative humidity can increase transpirational damage and lead to desiccation, increased respiration, and an unmarketable product (Kader, 1987). One of the benefits of MAP and packaging in general is the maintenance of adequate relative humidity within the package. There is a danger that the relative humidity can get too high, causing moisture condensation and conditions favorable for microbial growth, resulting in decay of the commodity. Condensation on the film package surface may adversely affect the gas permeability properties of the film, leading to the evolution of an unfavorable atmosphere. Maintenance of proper temperature throughout the postharvest handling steps is central to preventing condensation within packages.

6. Optimum Concentrations of O₂ and CO₂. An optimum atmosphere should minimize respiration rate without danger of metabolic damage to the commodity. Different commodities vary widely in their tolerances to different atmospheres. A classification of fresh fruits and vegetables according to their tolerance to reduced O₂ and elevated CO₂ has been presented elsewhere (Kader et al., 1988). Because the effects of low O₂ and high CO₂ on respiration are additive, the optimal concentrations of both gases in combination are difficult to predict without actual measurements in a variety of atmospheres (Fig. 2). The limits of tolerance to low O₂ and high CO₂, beyond which damage occurs, are subject to several variables such as temperature, physiological condition, maturity, and previous treatment. Since atmospheres within a package may fluctuate slightly, the practical ‘optimal’ atmosphere should be one that is not too close to an injurious atmosphere.

- Environmental Factors are discussed below.

1. Temperature and Relative Humidity. Ambient temperature will affect commodity temperature through the mediation of the intervening film. The commodity will both cool and warm more slowly than it would if it were exposed directly to ambient conditions. Temperature changes also affect the permeability of the film. In general, film permeability increases as temperature increases, with CO₂ permeability responding more than O₂ permeability. This implies that a film that is appropriate for MAP at one temperature may not be appropriate at other temperatures. This once again reinforces the importance of careful temperature management of packaged produce.
Relative humidity appears to have little effect on permeability of most film packages unless actual condensation occurs on the film. Most common films are relatively good barriers to moisture vapor (Kader et al., 1988), because they maintain high internal humidity even in dry, ambient conditions.

2. Light. For many commodities, light is not an important influence in their postharvest handling. However, green vegetables, in the presence of sufficient light, could consume substantial amounts of CO₂ and produce O₂ through photosynthesis. These reactions would antagonize the processes of respiration which are aiding in the maintenance of a specified MA within the package. There is little available information concerning whether ambient light passing through a plastic film is sufficient to cause substantial photosynthesis, but it bears investigation. Specific commodities may be adversely affected by light, though not through photosynthesis. Greening of potatoes and Belgian endive can cause serious loss of quality unless light is excluded. For such commodities, opaque packages may be appropriate.

3. Sanitation Factors. Packaging fresh fruits and vegetables in plastic films can create a high-humidity, low-oxygen environment that is favorable to pathogenic microorganisms that would not otherwise thrive. Because some of these are of public health concern (Brackett, 1987; Hintlian and Hotchkiss, 1986), care must be exercised to ensure proper sanitation and to avoid conditions favorable to the growth and reproduction of such microorganisms. For example, Clostridium botulinum, the cause of botulism, thrives in high moisture, low salt, low acid, and low oxygen conditions above 3.3°C. It has been estimated that 53% of botulism outbreaks are associated with vegetables (Pierson and Reddy, 1988). Most of these have been associated with home canning, but commercially processed foods were involved in 8.6% of the reported cases of botulism (Pierson and Reddy, 1988). With the exception of mushrooms (Sugiyama and Yang, 1975), fresh vegetables have not previously been implicated in botulism because of the bacterium's requirement for anoxic conditions. Such conditions could be created in a MAP that became anaerobic, perhaps due to storage at a higher-than-expected temperature. Although it is likely that the anoxic conditions necessary for growth of the bacterium would cause such loss of quality of the produce as to render it unsalable, this fact is yet to be established and should be investigated.

The high humidity maintained within MAP may enhance the growth of plant pathogens, such as Botrytis and Geotrichum. For this reason, fungicidal treatment of packaged fruits and vegetables is very important. However, consumer expectations of reduced use of chemicals, especially postharvest applications, make such treatment increasingly difficult.

Methods of Creating Modified Atmosphere Conditions

Modified atmospheres can be created either passively by the commodity or intentionally, as described below.

- **Commodity-Generated or Passive MA.** If commodity characteristics are properly matched to film permeability characteristics, an appropriate atmosphere can passively evolve within a sealed package as a result of the consumption of O₂ and the production of CO₂ through respiration (Smith et al., 1987). In order to achieve and maintain a satisfactory atmosphere within a package, the gas permeabilities of the selected film must be such that they allow O₂ to enter the package at a rate offset by the consumption of O₂ by the commodity. Similarly, CO₂ must be vented from the package to offset the production of CO₂ by the commodity. Furthermore, this atmosphere must be established rapidly and without danger of the creation of anoxic conditions or injuriously high levels of CO₂.

- **Active Modified Atmosphere.** Because of the limited ability to regulate a passively established atmosphere, it is likely that atmospheres within MAP will be actively established and adjusted. This can be done...
by pulling a slight vacuum and replacing the package atmosphere with the desired gas mixture. This mixture can be further adjusted through the use of absorbers or adsorbers in the package to scavenge O₂, CO₂, or C₂H₄. Some of the common gas adsorbers have been described (Kader et al., 1988).

Although active modification implies some additional costs, its main advantage is that it ensures the rapid establishment of the desired atmosphere (Fig. 4). In addition, ethylene adsorbers can help to ensure the delay of the climacteric rise in respiration for some fruits. Carbon dioxide absorbers can prevent the build-up of CO₂ to injurious levels, a situation that can occur for some commodities during passive modification of the package atmosphere (Zagory and Kader, 1988).

Films Available for Modified Atmosphere Packaging of Fresh Produce

Although many plastic films are available for packaging purposes, relatively few have been used to wrap fresh produce. Even fewer have gas permeabilities that make them suitable to use for MAP. Because O₂ content in a MA package is typically being reduced from an ambient 21% to 2–5% within the package, there is a danger that CO₂ will increase from ambient 0.03% to 16–19% in the package. This is because, normally, there is a one-to-one correspondence between O₂ consumed and CO₂ produced. Because these high levels of CO₂ would be injurious to most fruits and vegetables, an ideal film must let more CO₂ exit than O₂ enter. The CO₂ permeability should be somewhere in the range of 3–5 times greater than the oxygen permeability, depending upon the desired atmosphere. Several polymers used in film formulation meet this criterion (Table 1). Of these, low-density polyethylene and polyvinyl chloride are the main films used in packaging fruits and vegetables. Polystyrene has also been used, but Saran™ and polyester have such low gas permeabilities that they would be suitable only for those commodities with very low respiration rates.

### Mathematical Models of Modified Atmosphere Packaging

Several workers have attempted to model the interactions between respiring produce and package atmosphere in an effort to put the design of MAP on an analytical basis. Their efforts have been reviewed (Kader et al., 1988). None of the models to date have been comprehensive and general enough to include all of the salient variables (Table 2). Most attempts at modeling recognize the interaction of respiration by the commodity and the permeation of respiratory gases through the package. When the gas flux due to respiration equals the gas flux due to permeation, the package will be at equilibrium. In order to predict what this equilibrium will be and how long it will take to achieve, a model should take into account at least: (1) the effects of changing O₂ and CO₂ concentrations on respiration rate; (2) the possibility that the RQ is not equal to 1; (3) the permeability of the film to O₂ and CO₂; (4) the effect of temperature on film permeability; (5) the surface area and head space of the package; (6) the resistance of the commodity to diffusion of gases through it; and (7) the optimal atmosphere for the commodity of interest. In addition, in order to be of

![Fig. 4.—Relative Changes in CO₂ and O₂ Concentrations during Passive Modification and Active Modification on the package around the commodity](image-url)
maximum utility, a model should recognize when certain gas concentrations are deleterious to the commodity and if they are likely to be reached before or during equilibrium, the model should inform the user of the potential problem. No model to date has integrated all of these variables.

In collaboration with J. Mannapperuma and R.P. Singh (Dept. of Agricultural Engineering, University of California, Davis), we have been working on a model of MAP that is intended to be of general use for any fresh fruit or vegetable. The model uses respiration rates at several oxygen concentrations and assumes respiration kinetics follow a linear combination of zeroth and first order behavior, to simulate changes in the atmosphere inside a package of specified dimensions and permeabilities. Other than respiration values and permeabilities, the model requires inputs of desired O₂ and CO₂ concentrations, ambient or initial gas concentrations, the mass of commodity inside the package, the free volume in the package, and the diffusion resistance values for a particular commodity. Using this information, the model solves a series of linear and nonlinear ordinary differential equations to predict equilibrium gas concentrations both within the package and within the commodity (these values may differ initially for commodities with high gas diffusion resistance), and the time course of gas concentration changes within the package and the commodity. If permeability values for a number of films are available, the model will suggest which film would be most appropriate for packaging the commodity of interest and predict what the equilibrium atmosphere would be. Alternatively, the model will calculate the permeability characteristics required for an ideal film to achieve a desired atmosphere for the commodity.

The utility of the model is its ability to answer 'what if' questions concerning changes to any of the input variables. A number of rapid simulations can rule out many potential packaging scenarios, thus saving time in testing and development. Preliminary testing of the model has shown that it can accurately predict equilibrium O₂ concentrations for any of the commodities we have tested (including several cultivars of broccoli, green bean, pear, and tomato). However, the model has a tendency to underestimate package CO₂ concentrations.

We are currently modifying and refining the model to make it more generally applicable. For example, the model does not include estimates of RQ. It assumes an RQ of one, but, if RQ were greater than one, the model would underestimate CO₂ production, which we observe. The model does not explicitly include temperature as a variable. Inputs of respiration and film permeabilities are assumed to have been generated at the temperature that the package will experience. This information, particularly film permeabilities at desired temperatures, is not always available. We are currently involved in measuring gas permeabilities of several common films at a number of temperatures so that we can estimate permeabilities at any temperature. In addition, the model does not require inputs on the effect of elevated CO₂ concentrations on respiration. However, the effects of elevated CO₂ on respiration can be implicitly included in the data for respiration at different O₂ concentrations by using respiration data generated in the presence of elevated CO₂ combined with reduced O₂ (Fig. 2). We have assembled a large computer database of postharvest requirements and recommendations for over forty fruits and vegetables in order to develop and test the model. This database includes information on respiration under various O₂ and CO₂ regimes as well as commodity diffusion resistance values and optimal atmospheres for storage.

**Future Research Needs**

Current attempts at understanding and modeling the dynamic processes in an MA package are hampered by a lack of data in some cases. Most data on film permeability have been generated at a single temperature and relative humidity. Although current information suggests that relative humidity has little effect on permeability of hydrophobic plastic polymers, changes in temperature certainly do change permeability values. Furthermore, permeabilities to different gases change by different amounts in response to temperature changes. It would be helpful if manufacturers of flexible plastic films measured permeabilities at several temperatures that are appropriate to the storage of fruits and vegetables. This information would make any model more accurate.

For many commodities, there is little information available on respiration rates in several combinations.
of O₂ and CO₂ concentrations. Such measurements are time-consuming but necessary to the accurate prediction of respiration rates in desired atmospheres. Gas diffusion resistance information is very scanty for most fruits and vegetables. Yet this information is important to understanding how an atmosphere is evolving inside the commodity, not just inside the package headspace. More research is needed into the use of gas adsorbers and scavengers inside packages and how they can aid in the maintenance of a desired package atmosphere.

On a broader front, the place of MAP in the general produce distribution system needs to be studied and the feasibility of altering handling practices to accommodate MAP should be investigated. Methods of ascertaining the quality of packaged produce without violating the integrity of the package must be devised. Perhaps small indicators of temperature and atmosphere could be included in such packages. Also, researchers need to find suitable nonchemical methods of disease control in order to meet the challenges created by the unique environment of a MAP for commodities that do not tolerate elevated fungistatic levels of CO₂. With the availability of such techniques, it will become more likely that MAP can be used as a practical alternative to costly QA facilities and aid in maintaining the physical and flavor qualities of fresh produce.

References


—Edited by Judie D. Daiezah, Associate Editor