Modified Atmosphere and Vacuum Packaging to Extend the Shelf Life of Respiring Food Products

L.G.M. Gorris and H.W. Peppelenbos

Summary. There has been a recent upsurge in the application of modified atmosphere and vacuum packaging to extend the shelf life of food products that rapidly deteriorate. Although these techniques are mostly used with nonrespiring products, both offer considerable prospects for respiring products as well. Because not all commodities respire at the same pace, packaging conditions, such as the initial gas atmosphere applied, the type of packaging material used, and the storage temperature, require special consideration. Choosing the wrong packaging conditions may lead to loss of product quality and also may impair the microbiological safety normally associated with fresh fruits and vegetables. This paper stresses the importance of these considerations with modified atmosphere and vacuum packaging systems.

The postharvest quality of perishable, respiring foods like agricultural and horticultural commodities can be stabilized by altering the atmosphere surrounding a product using controlled atmosphere (CA) storage facilities. These technically complex and rather expensive facilities continuously adjust the composition of the atmosphere to the optimal concentrations programmed; they are mostly applied for large-scale storage. With modified atmosphere (MA) storage, there is no active control over the atmospheric composition, which starts from a defined initial gas composition but is subject to changes due to physiological activity of the product and the characteristics of the physical environment [e.g., composition of the gas atmosphere, temperature, relative humidity (RH)]. Current applications of CA and MA technologies include long-term storage of ap-

ples, pears, kiwifruits, and cabbage, temporary storage of strawberries, cherries, and bananas (Kader et al., 1989) and shipment of lettuce.

Modified-atmosphere packaging (MAP) has proven to be a quite flexible, small-scale means of extending the shelf life of fresh foods (Figs. 1 and 2). With nonrespiring foods like meat, cheese, or peanuts, modifying the atmosphere would involve replacing the normal headspace within a packaged product with a specific atmosphere. The atmosphere is commonly composed of N_2 , O_2 , and CO_2 . Although ordinary air consists mainly of these three gases (78% N_2 , 21% O_2 , 0.04% CO_2), the beneficial effect of MAP is obtained by applying the gases in an altered ratio, which may be different for different products (Table 1). The shelf life of nonrespiring products is prolonged because the two most important types of deterioration—physicochemical deterioration (e.g., browning of meat due to the action of oxygen) and microbial deterioration (e.g., the growth of molds in cheese and bakery products)—are blocked or prevented. High gas barrier films or laminates are used to exclude gas exchange through the package, which would result in a less beneficial in-package gas atmosphere.

In contrast to the nonrespiring products, fresh and freshly processed vegetables and fruits stay metabolically active after harvest, and this activity is essential for retaining their quality. To extend the shelf life of respiring products through MAP, a suitable packaging system must be composed of a gas atmosphere that allows for a basic level of metabolism, which means that a certain amount of O_2 should be available. The basic level of metabolism varies greatly with different commodities (type, maturity) and depends also on the degree of processing (trimming, cutting, slicing, etc.). Because the composition of the gas atmosphere is the result of the initial gas atmosphere composition, the gas exchange through the package, and the respi-

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Agrotechnological Research Institute, Haagsteeg 6, P.O. Box 17, NL-6700 AA Wageningen, the Netherlands. tel: +31-8370-75000; fax: +31-8370-12260; E-mail: POSTMASTER%ATO.AGRO.NL

Fig. 1. *Modified atmosphere packaged apples.*

Fig. 2. *Modified atmosphere packaged, minimally processed vegetable mixtures.*

ratory activity of the product, it will change during the course of the storage period until an equilibrium is reached between gas exchange and gas consumption or production.

Fruits and vegetables are characterized by an elaborate microflora, consisting of many different types of bacteria, molds, and yeasts, most of which are involved in the spoilage of produce but are harmless to humans. Microorganisms that are dangerous to humans (pathogens that cause intoxications or infectious diseases) normally cannot establish a dangerous population density because they have to compete with the spoilage microflora. However, packaging the produce changes the microenvironment perceived by the microorganisms and may well impair this safe balance. As outlined below, the choice of the packaging system for respiring products must be carefully considered, taking into account the characteristics of the commodity, including the microbiological safety situation, and of the packaging system.

Vacuum packaging (VP) may be regarded as a special type of MAP, since part of the normal headspace is withdrawn, leaving an altered initial atmosphere. VP of respiring produce was first successfully practiced with a system designed by S. Burg almost a quarter of a century ago (Burg, 1975; Burg and Burg, 1966). Although the system performed rather well, it was technically complex and never as widely adopted as CA or MA storage. A very simple VP system, designated as a moderate VP system, has recently been introduced in the Netherlands. In this system, perishable commodities are stored at ≈ 400 mBar in a

refrigerator. The system is currently being tested and will be discussed later as a technically simple alternative to MAP.

Modified Atmosphere Packaging of Respiring Products

Nonrespiring products often are packaged with no O_2 , but respiring products must have O_2 to produce enough energy to maintain their integrity and quality through the process of aerobic respiration, in which carbohydrates are converted to CO_2 and water at the expense of O_2 . When the O_2 level falls under a certain minimum or CO_2 accumulates over a maximum, the product will have to generate energy through anaerobic respiration, the end products of which (ethanol, acetaldehyde) cause off-flavors and loss of quality. From Table 2, which lists these tolerance limits for a range of vegetables and fruits, it may be evident that the variation in the limits is substantial among the various products.

MAP and VP slow down the metabolic activity of a product and of the microorganisms present, both spoilage and pathogenic, by limiting the O_2 supply and applying an elevated level of CO_2 . Because the same strategy underlies refrigerated storage, MAP and VP of respiring produce are usually combined with this technique. Many commodities, e.g., avocados, mangoes, papayas, and cucumbers, are very sensitive to low-temperature injury and should not be stored below $\approx 13^\circ C$. Commodities like apples, broccoli, and pears are not sensitive to chilling and can be stored near $0^\circ C$ without ill effect (Zagory and Kader, 1988).

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Table 1. *Recommended storage conditions for some nonrespiring and respiring food products (Lioutas, 1988).*

Food product	Temp ($^\circ C$)	Vol O_2 (%)	Vol CO_2 (%)	Vol N_2 (%)
<i>Nonrespiring</i>				
Thin-sliced meat	0–2	0	80	20
Red meat	0–2	30	30	40
White fish	0–2	30	40	30
Chicken	0–2	0	30	70
Chilled cooked meals	0–2	0	20	80
Cheese	0–2	0	0	100
Pasta	0–5	0	60	40
Bakery products	20–22	0	100	0
<i>Respiring</i>				
Lettuce	0–5	2–5	0–2	Balance
Apple	0–5	2–3	1–2	Balance
Broccoli	0–5	1–2	5–7	Balance
Strawberry	0–5	10	15–20	Balance
Mushroom	0–5	21	10–15	Balance
Tomato	8–12	3–5	0	Balance
Banana	12–15	2–5	2–5	Balance
Avocado	5–13	2–5	3–10	Balance

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Considering the variability in the levels of respiration activity, tolerance to O₂ and CO₂, and chilling injury for individual vegetables and fruits, optimal packaging material would be tailor-made. Some packaging-film manufacturers indeed claim the ability to tailor-make films for any commodity by physically modifying existing films or by manufacturing films with the desired specifications. However, the logistics of food processing and packaging companies may make it impractical if they need to use many different films to package the range of products. Still, the range of packaging materials continues to increase. To facilitate the choice of packaging conditions, researchers of the Agro-technological Research Inst. began compiling a rather distinctive computer database that interlinks data on product physiology, product quality, and packaging material characteristics. Data on individual and combinations of factors will all be determined under a number of practical MAP storage conditions and will not rely on, for example, in the case of the packaging materials, specifications provided by manufacturers. The database will enable one to choose the packaging material best suited for a product, considering its type and degree of maturity and processing. It will be developed using model products from several classes of commodities, classified according to key parameters such as respiratory activity and tolerances to chilling or gases (Peppelenbos, 1992).

Packaging

When respiring products are to be packaged, the initial gas atmosphere may be composed of pure gases or of ordinary air, which is technically simpler and cheaper. Because the packaged product will respire actively, the initial gas atmosphere will change during storage. Oxygen will be consumed and CO₂ and H₂O will be produced. Thus, the O₂ level

will drop and the CO₂ level rise. Using a high-barrier package film, O₂ will be fully depleted, the product will switch to anaerobic respiration, and quality will be lost. Respiring products, therefore, need to use the recently developed types of semi-permeable or low-barrier films. Low-barrier films currently available have variable gas permeability specifications. As shown in Table 3 for a small selection of films, there is about one magnitude difference in the permeability for O₂ and CO₂ between individual films. Ultra-low-barrier, microperforated films are being developed that have air permeabilities of $\approx 60,000$ liters/m²·day·atmosphere. These films are probably well-suited for packaging products with extremely high respiration rates, like asparagus, broccoli, mushrooms, mung bean sprouts, and shredded vegetables.

The equilibrium gas composition is determined by the gas permeabilities and respiratory activity of the packaged product and the storage temperature. Gas permeability specifications given by film manufacturers are usually determined under conditions that are remote from the high-humidity, refrigerated storage conditions of respiring produce. At present it is impossible to tell from the specifications provided by a packaging film manufacturer whether a specific film would provide for an in-package gas atmosphere with tolerable O₂ and CO₂ levels when applied in practice. Thus, the suitability of a film must be tested with the product under the correct practical conditions. Figure 3 depicts the result of such a test with tomatoes, using either oriented polypropylene or K-resin, a butadiene-styrene copolymer, for packaging. Taking into account the tolerance limits for O₂ and CO₂ (Table 2), the equilibrium O₂ level is too low, whereas the CO₂ level is much too high with the 15- μ m polypropylene film. The 25- μ m K-resin film gives a reasonable but not yet optimal equilibrium gas composition with O₂ at $\approx 4\%$ to 6% volume and CO₂ at 4% to 5%

Table 2. Tolerance of respiring commodities to low O₂ or high CO₂ levels, determined at the optimal storage temperature of each product (Kader et al., 1989).

Vol (%)	Minimal O ₂ level	Vol (%)	Maximal CO ₂ level
	Product		Product
0.5	Nuts, dried fruits, and vegetables	1	Lettuce
1	Broccoli, mushrooms, garlic, onion, most cut or sliced fruits and vegetables	2	Golden Delicious apples, grapes, apricot, tomato, endive, artichoke, celery, sweet potato
2	Apricot, kiwifruit, cherry, nectarine, peach, plum, strawberry, pineapple, most apples and pears, sweet corn, lettuce, celery, green beans, cabbage, cauliflower, brussels sprouts	5	Peach, plum, nectarine, orange, banana, avocado, kiwifruit, green pea, eggplant, cauliflower, cabbage, brussels sprouts, radish, carrot, chicory
3	Avocado, tomato, pepper, cucumber, artichoke	10	Pineapple, lemon, cucumber, asparagus, green beans, broccoli, leek, onion, garlic, potato
5	Citrus fruits, green pea, asparagus, potatoes	15	Strawberry, blackberry, cherry, fig, sweet corn, mushroom, spinach, kale

Fig. 3. Dynamics of the gas composition for whole tomatoes packaged under air with two different films and stored at 10C (data from Geeson et al., 1985).

(Geeson et al., 1985). The above-mentioned computer database may well replace the laborious testing of the suitability of available types of films every time a new fresh or freshly processed food needs to be packaged.

Many packaging materials with favorable gas permeability characteristics have a rather low permeability for water vapor. This may be a complicating factor, because in most instances the RH in a package is very high (295%). Any small fluctuation in the storage temperature may result in condensation, which would greatly increase the proliferation and spread of spoilage microorganisms. Especially in fruits, high RH causes heavy losses due to microbial decay. In-package RH may be controlled by using packaging materials with high water vapor permeabilities, by including sachets with water absorbers like CaCl_2 , sorbitol, or xylitol in the package, or by using packaging material with suitable gas permeability that has been coated with these desiccants (Barmore, 1987; Shirazi and Cameron, 1992).

Another complicating factor is the phytohormone ethylene, which is involved in the ripening or maturation of a product. In a

MAP system, the ethylene produced by the packaged product may accumulate to some extent, since the permeability of most packaging films for ethylene is about halfway between that for CO_2 and O_2 . Alternatively, ethylene may enter a package from the outside when there is a prominent source there, like with ripening climacteric fruits. Many premature fruits, green vegetables, and some cut flowers are sensitive to ethylene, which speeds their ripening and thus shortens their shelf life. Inclusion of ethylene scrubbers like potassium permanganate may counteract the effect of ethylene, although the capacity of such gas scavengers is finite.

Microbiological Safety

Fresh fruits and vegetables normally have an elaborate spoilage microflora, due to intensive contact with various types of microorganisms during growth and postharvest handling. The high acidity of many fruits ($\text{pH} \leq 4.6$) limits spoilage due to acid-tolerant molds, yeasts, and lactic-acid bacteria. Vegetables generally have a pH around 6.0 to 7.0

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Table 3. Thickness and gas permeabilities of some semipermeable packaging films, at 20-25C and varying relative humidity (data provided by manufacturers).

Film	Thickness (μm)	Permeability (liters/ $\text{m}^2 \cdot \text{day} \cdot \text{atmosphere}$)	
		O_2	CO_2
Polyvinylchloride	14-18	15-20	80-120
Ethylenevinylacetate	10-25	13-32	53-134
Low-density polyethylene	25-50	3-6	10-20
Polystyrene	50	3-4	13
Oriented polypropylene	15	2,6	7,5
K-resin	25	4,4-4,8	37,1
Cellulose acetate	40	1,5-3	15

Fig. 4. Small-scale moderate vacuum storage system (Vacu Products b.v., Delft, the Netherlands) with mung bean sprouts. The piston shown is used to evacuate the container through a rubber stopper by band.

and lack this intrinsic protection. Microbial spoilage of undamaged, healthy products can only be effectuated by microorganisms able to penetrate the skin, which requires the presence of specific enzyme systems. With vegetables, pectinolytic types of gram-negative bacteria of the genera *Pseudomonas* and *Enterobacter* are often involved in spoilage. Spoilage microorganisms usually pose no safety problem for consumers, in fact they may prevent potentially hazardous pathogens from growing to dangerous levels through competition for oxygen, carbohydrates, other nutrients, and space—a mechanism often referred to as competitive exclusion. However, refrigerated MAP storage may impair the safety balance. Refrigeration slows the growth of the spoilage flora, most of which are mesophiles and grow best at temperatures between 20 and 40C, and re-

duces their competitive capacity. Psychrophilic pathogens like *Listeria monocytogenes*, *Yersinia enterocolitica*, enterotoxigenic *E. coli*, *Aeromonas hydrophila*, *Clostridium botulinum* type E, and nonproteolytic strains of *C. botulinum*, which are able to grow at temperatures as low as 3 to 5C, may then get a chance to proliferate. If inappropriate temperatures are used, even mesophilic pathogens such as *Salmonella typhimurium*, *Staphylococcus aureus*, and *Bacillus cereus* may rapidly develop.

Moderate Vacuum Packaging

Moderate vacuum packaging is a new type of the VP technique designed by Burg (1975; Burg and Burg, 1966). In the Burg system, produce is stored under an atmospheric pressure in the range of ≈ 10 to 100 mBar at refrigerated temperatures. At this low pressure, a constant circulation of fresh air, substantially saturated with water (RH 80% to 100%), is maintained. Facilities to constantly scrub CO₂ and ethylene may be included. In the moderate VP system, storage is at ≈ 400 mBar, and the composition of the atmosphere is not actively controlled. The atmospheric pressure is reduced by simply evacuating the air from the storage facility. This reduces the amount of O₂ in the storage atmosphere, slows the respiration rate of the stored produce, and inhibits growth of microorganisms. Any O₂ consumed is converted to CO₂. Figure 4 shows a small-scale moderate VP system designed by Vacu Products b.v. (Delft, the Netherlands). MAP requires rather sophisticated equipment and is often used to prepare once-only packages, but the moderate VP system is technically simple and, when used in a rigid-container version, may be recycled. Investigations at our institute (Gorris and de Witte, unpublished) have shown that the shelf life of a perishable commodity such as mung bean sprouts may be extended from 2 to 6 days when stored at 400 mBar and 4 to 7C. The system also prevented enzymatic browning of

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Table 4. Gas composition of fresh potato strips packaged under 5% O₂ and 10% CO₂ during storage at 5C (O'Beirne and Ballantyne, 1987).

Film	Gas composition in package (vol, %)			
	Day 2		Day 6	
	O ₂	CO ₂	O ₂	CO ₂
Surlyn/PVdC coated polyester ^a	0-1	8-9	0	9-10
Low-density polyethylene (55 μ m)	0-1	13-15	0	7,5-8,5
RMF-A (plasticized PVC)	6-7	1-1,5	5-9	1,5-2
Low-density polyethylene (25 μ m)	1,5-2	3,5-4,5	2-2,5	4-4,5

^aHigh-barrier laminate containing PVdC polyvinylidene chloride.

cut vegetables and fruits. The safety of the moderate VP system regarding survival and growth of pathogenic bacteria and the type of produce for which the system is best suited are currently being investigated.

Safe Packaging

In developing a MA package, the objective is to match the respiration rate of the commodity to the gas permeability of the packaging. Inappropriate packaging material may pose quality and even health problems, as can be illustrated with the data from O'Beirne and Ballantyne (1987) on packaging of fresh potato strips (Table 4). A package suited for this product would create an equilibrium gas composition of 1% to 2% O₂ and 3% to 5% CO₂ to prevent enzymatic browning and retard senescence. In two cases, the in-package level of O₂ rapidly declines to zero, which may initiate off-flavor development due to anaerobic respiration. A third film did not reduce O₂ enough to inhibit enzymatic browning, and the fourth rendered a satisfactory gas composition. In the first two cases, a potential health hazard exists in that the soil-borne anaerobic pathogen *Clostridium botulinum* can grow and produce toxin at the prevailing low-oxygen situation that suppresses the competitive action of the spoilage flora. Although only certain strains of *C. botulinum* thrive well at zero O₂ under MAP conditions, all of the pathogens mentioned before have potential to survive in either an anaerobic or a low-oxygen MAP atmosphere.

In potato strips, oxygen depletion causes loss of product quality that would probably keep consumers from eating the potentially hazardous foods. But such an organoleptic warning signal may not always occur, as in the case of overwrapped mushrooms stored at ambient temperatures. This condition may produce anaerobic conditions and support growth and toxin production of *C. botulinum* while the product is still of acceptable quality (Sugiyama and Yang, 1975). *Clostridium botulinum* may be effectively controlled by maintaining a low level of O₂ ($\pm 1\%$ to 2%) in the package, by choosing the correct packaging material, and by adequately refrigerating the product throughout the production-to-retail chain.

Up to now MAP and VP storage of vegetables have enjoyed a period of comparative safety. However, MAP and VP may at times inhibit the growth of the endogenous spoilage flora, thus diminishing a key signal by which consumers can tell a spoiled product. These storage methods will not eliminate pathogens but, under the right circumstances, will even select for their outgrowth, especially during long-term storage and in combina-

tion with temperature abuse, while the packaged product may still look organoleptically sound. Because the interplay of product physiology, microbiology, and packaging conditions will eventually create the "right conditions," more fundamental knowledge on these factors, individually and in combination, should be gathered, and packaging conditions should be carefully considered to prevent such hazards. If these conditions are followed, MAP and VP of intact, minimally processed vegetables and fruits may safely expand in retail as well as catering sectors to comply with consumer demand for premium-quality, wholesome foods.

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