Controlled atmosphere, modified atmosphere and modified atmosphere packaging for vegetables

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Abstract
Purpose of Review: This review is aimed at illustrating the directions in which research on controlled atmosphere (CA), modified atmosphere (MA) and modified atmosphere packaging (MAP) for fresh and fresh-cut vegetables has been focused since about 2000, and to highlight significant new findings in the field.

Findings: In the last 5 years, little research with vegetables has been carried out to attempt to elucidate the underlying physiological and biochemical mechanisms related to the effects of CA and MA on produce. In contrast, there have been several applications of CA, MA and MAP to a surprisingly large number of previously underexploited vegetables and fresh-cut vegetable products; the potential for using superatmospheric O₂, primarily in MAP, has also been extensively evaluated. Coincident with the continuing development of fresh-cut products, there has been great interest in how the growth of microbial pathogens can be controlled in MAP.

Limitations/implications: Since little economic incentive exists for long-term CA or MA storage of most vegetables, recent research has been more focused on using MAP for better quality maintenance within existing supply chains. The main limitations of more successful application of MAP are the seemingly inherent problem of fluctuating temperatures that occurs during distribution, and problems with mixed loads of different products held at compromise temperatures, both of which interfere with the maintenance of proper package atmospheres.

Directions for future research: Understanding the basic mechanisms that explain vegetable product tolerance to different gas atmospheres could help to streamline the optimisation of MA systems for new products. Feedback systems that allow atmospheres to be adjusted in response to indications of product stress could replace current static MA systems and address the problem of fluctuating temperatures.

Keywords: Controlled atmosphere; modified atmosphere; modified atmosphere packaging; superatmospheric oxygen; fresh-cut; food safety

Abbreviations
CA Controlled Atmosphere
MA Modified Atmosphere
MAP Modified Atmosphere Package/Packaging

Introduction
The amount of research on controlled atmosphere (CA), modified atmosphere (MA) and modified atmosphere packaging (MAP) of vegetables has historically lagged behind that of fruits, and most of the research carried out with vegetables has been focused on a few crops, i.e., lettuce (Lactuca sativa), onion (Allium cepa) and tomato (Solanum lycopersicum). Thompson [1**] reviewed the recommended CA and MA conditions for most crops for which such research has been conducted. The United States Department of Agriculture’s Agriculture Handbook 66 (available online at http://www.ba.ars.usda.gov/hb66/), which was completed in 2002 and revised in 2004, also contains overviews of CA [2] and MAP [3], as well as recommended CA conditions in the individual commodity chapters. Fonseca et al. [4*] re-
viewed the modelling of the respiration rate of fresh fruits and vegetables for designing MAP systems.

Most of the research on CA, MA and MAP involves empirical observations of changes in various shelf-life limiting quality factors over time in experiments that involve placing a product in several combinations of gas atmospheres and sometimes also different temperatures. Reports of MAP experiments in which a vegetable product is placed in a number of packages and the shelf-life observed and compared are not particularly useful unless the packaging materials were selected because they were expected to create particular desired gas atmospheres that can be of benefit to the product. Not included in this review are those papers in which MAP was used, but gas concentrations in the packages were not reported.

In 2003, Saltveit asked, “Is it possible to find an optimal controlled atmosphere?” [5**]. His contention was that searching for a single, invariable and constant set of storage conditions for each inherently variable and dynamic biological system (ie, fruit or vegetable) has not proven to be very successful in many cases. He proposed that CA systems should also be dynamic, that is, they should measure and respond to the commodity’s changing metabolic state. One way that has been proposed in which variable environmental conditions during distribution could be addressed is by using a combination CA/MAP system during transportation [6**]. In this approach, the MAP is designed to produce an optimal gas atmosphere during the higher temperature retail display period, while a surrounding gas atmosphere is selected for the lower temperature transportation period; this atmosphere interacts with the MAP to produce the optimal atmosphere within the packages during that portion of distribution.

**Mechanism of CA effects**

McKenzie et al. [7*] investigated the role of sugar metabolism in the observed inhibition of senescence in CA-stored broccoli (Brassica oleracea var. italica) and asparagus (Asparagus officinalis) by measuring glycolytic metabolites, the activities of sucrose-metabolising and glycolytic enzymes, and intracellular sugar concentrations. The results suggested that asparagus is more prone to irreversibly engage metabolic pathways linked to senescence-related increase in plasma membrane permeabil-

**CA, MA or MAP for underexploited vegetables**

In the past 5 years, there have been a few reports of the determination of useful atmospheres for CA storage of vegetables on which little previous work has been done including jicama (Pachyrhizus erosus) [8], Belgian endive (Cichorium intybus) [9], spinach (Spinacia oleracea) [10], green bean (Phaseolus vulgaris) [11, 12] and green celery (Apium graveolens) [13]. Recently, MAP systems have been developed for underexploited vegetables including white asparagus [14], prickly pear cactus stems (Opuntia spp.) [15, 16], fennel (Foeniculum vulgare) [17], artichoke (Cynara scolymus) [18], Belgian endive [19], ginseng (Panax ginseng) [20] and green celery [21].

Much more effort has been expended in recent years in searching for beneficial applications of MAP for fresh-cut products such as pumpkin (Cucurbita maxima) [22], rutabaga (Brassica napus var. napobrassica) [23], green onion (Allium cepa x A. fistulosum) [24], Galega kale (Brassica oleracea, var. sabellica) [25, 26], sweetpotato (Ipomoea batatas) [27, 28], kohlrabi (Brassica oleracea var. gongyloides) [29], sweetcorn (Zea mays subsp. mays) [30, 31], salad savoy (Brassica oleracea var. viridis) [32], cilantro (Coriandrum sativum) [33], shredded purple carrot (Daucus carota) [34], celery sticks [35], fennel [36] and wild rocket (Diplopteryis tenufolia) [37].

MAP systems have also been explored for mixed fresh-cut items including fresh coleslaw made from cabbage (Brassica oleracea, var. capitata) and shredded carrot [38], and a ready-to-cook fresh-cut vegetable mixture of parsley (Petroselinum crispum), beet (Beta vulgaris), spinach, zucchini (Cucurbita pepo), pumpkin, carrot, celery, tomato, savory cabbage (Brassica oleracea var. sabauda), leek (Allium porrum), onion, and rehydrated peas (Pisum sativum) and ‘Borlotti’ beans (P. vulgaris) [39].

**Innovative MAP designs**

**MAP achieved via semipermeable film, membrane patch and perforation**

Almost all MAP systems utilise a semipermeable plastic film to regulate flow of O2 into and CO2 out of the package. Fonseca et al. [40**, 41] described perforation-mediated MAP and showed how tube dimensions, tube location and package geometry affect gas transfer, while temperatures in the range 5–20°C do not. Either reducing the diameter of the tube opening or increasing the tube length restricts gas transfer. The ratio of CO2 to O2 mass transfer coefficient (0.81) is not affected by temperature, tube dimensions or tube placement. Paul and Clarke [42**] described the mathematical modelling of MAP systems using a combination of semipermeable film, membrane patch and perforations. This combination approach was shown to allow a wide range of gas atmospheres to be created in MAP. An additional benefit of using perforations in MAP that was mentioned is that convective transport of gases through perforations is useful for controlling the package free volume.

**Combination treatments**

Several papers have been published that report on combining irradiation treatment with MAP to improve whole or fresh-cut vegetable quality [43–47] and to control microbial con-
tamination (48–52). An attraction of this combination seems to be that, when irradiation is used as a cold pasteurisation treatment, the chances of recontamination occurring are minimised if the product is in a sealed MAP system.

McKellar et al. [53] reported that treating fresh-cut lettuce with chlorine for 30 s at 48°C, compared with the typical 4°C chlorine treatment, allowed for better quality retention using a lower CO₂ concentration in MAP. Fan et al. [54] showed that a 2-min, 47°C water treatment reduced the sensitivity of fresh-cut lettuce in MAP to the undesirable effects of irradiation. However, Delaquís et al. [55] reported that a 3-min, 47°C water treatment favoured the growth of Listeria monocytogenes and Escherichia coli O157:H7 on lettuce stored at 10°C but not 1°C. Heat treatment and MAP combination treatments have also been tested with fresh-cut green onion [56] and leek (Tsouvaltis et al., unpublished) to control leaf base discolouration, root growth and leaf growth (‘telescoping’).

Superatmospheric O₂

Following on the work by Day [57*], a number of investigators have reported on the response of various vegetables to storage in superatmospheric O₂ concentrations. However, after reviewing the literature, and based on their own experiences from investigating the use of superatmospheric O₂, Kader and Ben-Yehoshua [58*] found little support for the idea that superatmospheric O₂ is of much practical benefit for most fresh or fresh-cut vegetables. Jacobsen et al. [59*] concluded that superatmospheric O₂ MAP is most beneficial for fresh-cut vegetables such as celeriac (Apium graveolens var. rapaceum), mushroom (Agaricus bisporus) and endive, which are sensitive to enzymatic browning and spoilage by yeasts, but it is questionable how much of the reported benefit was due to elevated O₂ levels and how much was due to the elevated CO₂ (>20%) that developed quickly in the packages that were used. Additional reports appearing in the last 5 years include those by Amanatidou et al. [60], Allende et al. [61, 62], Escalona et al. [63], and Limbo and Piergiovanni [64].

Growth of microbial pathogens in MAP

It is well established that CA and MA can reduce the growth of various microorganisms on stored vegetables [65, 66]. Charles et al. [67], for example, reported that both active and passive MAP with equilibrium atmospheres of 3% O₂ + 5% CO₂ reduced total aerobic mesophile, yeast and mould population growth, with active MAP giving better inhibition of Pseudomonas spp. and Enterobacteriaceae. Beuchat [68**], however, highlighted the potential for not only survival but also growth of human pathogens on raw, especially fresh-cut, produce. It was suggested that MAP, almost universally used with fresh-cut vegetables, could favour the survival or proliferation of human pathogenic microorganisms by limiting competition from the natural microbial population and extending the potential shelf-life of fresh-cut products – potentially allowing populations of pathogens to reach levels of significant risk. A number of papers have been published demonstrating the survival of L. monocytogenes, Salmonella enteritidis, E. coli O157:H7 and other pathogenic species on fresh-cut vegetables in MAP [69–75].

Drosinos et al. [76] reported that lactic acid bacteria were the predominant microorganisms on a Greek style tomato salad, and that the tissue pH dropped and organic acids increased more during storage in MAP than in air, but that there was no effect on survival of S. enteritidis. Tassou and Boziaris [77] reported that increased populations of Lactobacillus spp. did not prevent the survival of S. enteritidis on grated carrots in MAP irrespective of the amount of Lactobacillus spp. inoculum and despite the pH reduction caused by Lactobacillus. Geysen et al. [78] found that superatmospheric O₂ had no effect on the in vitro growth of Listeria innocua but that elevated CO₂ (12.5 or 25%) reduced the maximum specific growth rate and prolonged the lag time. Francis and O’Beirne [79] suggested that acid adaptation of Listeria spp. renders them more resistant to relatively high (25–30%) CO₂ atmospheres.

Conclusions and future directions

The rapid commercial growth in recent years of fresh-cut products, most of which are vegetables, has stimulated much applied research on MAP with regard to product quality retention and microbiological food safety concerns. The other major application of MA/CA for vegetables occurs during international transport. There is increasing awareness that optimum gas atmospheres can vary for any single commodity based on many factors, but especially the timeframe for distribution of the product. A better understanding is needed of the basic mechanisms that explain differences in vegetable product tolerance to different gas atmospheres and the indicators that product tolerance has been exceeded. This knowledge will help in the development of new CA, MA, and MAP systems that are able to respond to physiological and biochemical signals indicating product stress by continuously adjusting the gas atmosphere to minimise tissue metabolism in order to maintain the highest possible product quality during storage and distribution.

References

Papers of interest have been highlighted as:
* Marginal importance
** Essential reading


**The paper points out that for any given product, different atmosphere conditions may be required depending on the anticipated storage/transport length and temperature. It also describes a procedure for designing a combination CA/MAP system that produces optimal atmospheres during transport and for retail display conditions. Another example of this proposed MAP/CA system deals with its application to mixed loads of products with different atmosphere requirements.

**This review evaluates the different approaches that have been taken in modeling produce respiration for the design of MAP systems.


*Respiratory metabolism and sugar metabolism and compartmentation in air and CA conditions were investigated using broccoli and asparagus. Asparagus in CA appeared to engage the ethanolic fermentation pathway, while broccoli appeared to engage both the lactic and ethanolic fermentation pathways, but only transiently. The results allowed the authors to propose that CA may permit more controlled use of whichever vacuolar sugar the tissue normally uses (fructose in asparagus, sucrose in broccoli) and delays the senescence-related increase in plasma membrane permeability.


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**This paper should be read by any researcher working with CA, MA or MAP and the author’s points considered with regard to the relationship between product physiology and its gaseous environment.


**The paper points out that for any given product, different atmosphere conditions may be required depending on the anticipated storage/transport length and temperature. It also describes a procedure for designing a combination CA/MAP system that produces optimal atmospheres during transport and for retail display conditions. Another example of this proposed MAP/CA system deals with its application to mixed loads of products with different atmosphere requirements.


10 Mizukami Y, Saito T and Shiga T. Effects of controlled atmosphere on gus in CA appeared to engage the ethanolic fermentation pathway, while broccoli appeared to engage both the lactic and ethanolic fermentation pathways, but only transiently. The results allowed the authors to propose that CA may permit more controlled use of whichever vacuolar sugar the tissue normally uses (fructose in asparagus, sucrose in broccoli) and delays the senescence-related increase in plasma membrane permeability.


36 Escalona VH, Artes-Hernandez F and Artes F. Gas composition and temperature affect quality of fresh-cut fennel. HortScience
Breth / Stewart Postharvest Review 2006, 5:5

**Describes a method to design MAP that uses restricted diffusion through a pore or tube to achieve combinations of reduced O2 and elevated CO2 with radiation sensitivity of Listeria monocytogenes present in ready-to-use carrots (Daucus carota). Journal of Food Protection 2006:69:221–227.
**The authors show how a combination of a high flux membrane patch with higher CO2 concentrations than can be achieved using semipermeable plastic films.
**The authors show how a combination of a high flux membrane patch with perforations in a semipermeable film package offers a versatile route to create whatever O2 and CO2 environment may be needed for a given product. Detailed mathematical models are developed for describing and designing such systems.
**This review article describes the scientific rationale behind using superatmospheric O2 in MAP for fresh-cut produce, and it is asserted that this approach is particularly effective at inhibiting enzymatic tissue discoloration, preventing anaerobic fermentation reactions, and inhibiting microbial growth. The author suggests that superatmospheric O2 in MAP is capable of overcoming many of the perceived shortcomings of low O2 MAP.
*An alternative opinion on the potential of superatmospheric O2 for produce, the authors review the literature and report on their own unpublished research, and conclude that the effects of superatmospheric O2 are highly variable, with numerous examples of completely opposite effects for different products. It is also suggested that the claimed inhibitory effects of superatmospheric O2 on the growth of microorganisms may be more or less dependent on the presence of elevated concentrations of CO2, which is a fungistatic gas.
*In this, the most thorough validation of the concept of superatmospheric O2 MAP for fresh-cut produce, mixed vegetable salad collected from a commercial processing plant was stored using the technique for 8 days at 4°C with two films tested, an initial O2 concentration of 95%, and inoculation with Listeria monocytogenes and Aeromonas caviae.
64 Limbo S and Pergiovanni L. Shelf life of minimally processed pota-
toes Part 1. Effects of high oxygen partial pressures in combination
with ascorbic and citric acids on enzymatic browning. Postharvest
65 Bennik MHI, Vorstman W, Smid EJ and Gorris LGM. The influence
of oxygen and carbon dioxide on the growth of prevalent Enterobacte-
riaceae and Pseudomonas species isolated from fresh and controlled-
66 Jacxsens L, Devlieghere F, Ragaert P, Vanneste E and Debevere J.
Relation between microbiological quality, metabolite production and
sensory quality of equilibrium modified atmosphere packaged fresh-cut
280.
67 Charles F, Sanchez J and Gontard N. Modeling of active modified
atmosphere packaging of endives exposed to several postharvest tem-
68 Beuchat LR. Ecological factors influencing survival and growth of
human pathogens on raw fruits and vegetables. Microbes and Infection
**This paper served to focus the attention of researchers, government regu-
lators and the fresh-cut industry on the potential for survival and growth of
human pathogens on fresh-cut produce, especially vegetables, and the possi-
bility of increased risk of food poisoning if treatments that extend the shelf-
life of fresh-cuts are not coupled with good agricultural practices and good
manufacturing practices to minimise the possibility of microbial contamina-
tion.
69 Francis GA and O'Beirne D. Effects of vegetable type, package atmos-
phere and storage temperature on growth and survival of Escherichia
coli O157:H7 and Listeria monocytogenes. Journal of Industrial Micro-
70 Francis GA and O'Beirne D. Effects of vegetable type and antimicro-
bial dipping on survival and growth of Listeria innocua and E. coli.
International Journal of Food Science and Technology 2002:37:711–
718.
71 Bagamboula CF, Uyttendaele M and Debevere J. Growth and survival
of Shigella sonnei and S. flexneri in minimal processed vegetables
packed under equilibrium modified atmosphere and stored at 7 degrees
72 Jacxsens L, Devlieghere F and Debevere J. Temperature dependence of
shelf-life as affected by microbial proliferation and sensory quality of
equilibrium modified atmosphere packaged fresh produce. Postharvest
Biology and Technology 2002:26:59–73.
73 Sanz S, Gimenez M and Olarte C. Survival and growth of Listeria
monocytogenes and enterohemorrhagic Escherichia coli O157:H7 in
minimally processed artichokes. Journal of Food Protection 2003:
66:2203–2209.
74 Bourke P and O'Beirne D. Effects of packaging type, gas atmosphere
and storage temperature on survival and growth of Listeria spp. in
shredded dry coleslaw and its components. International Journal of
75 Gomes BC and De Martinis ECP. Fate of Helicobacter pylori artifi-
cially inoculated in lettuce and carrot samples. Brazilian Journal of
Microbiology 2004: 35:145–150.
76 Drosinos EH, Tassou C, Kakimeno K and Nychas GJE. Microbi-
ological, physico-chemical and organoleptic attributes of a country
tomato salad and fate of Salmonella enteritidis during storage under
aerobic or modified atmosphere packaging conditions at 4 degrees C
77 Tassou CC and Boziaris JS. Survival of Salmonella enteritidis and
changes in pH and organic acids in grated carrots inoculated or not
with Lactobacillus sp. and stored under different atmospheres at 4
degrees C. Journal of the Science of Food and Agriculture 2002:
82:1122–1127.
78 Gysen S, Verlinden BE, Geeraerd AH, Van Impe JF, Michiels CW
and Nicolai BM. Predictive modelling and validation of Listeria in-
ocua growth at superatmospheric oxygen and carbon dioxide concen-
345.
79 Francis GA and O'Beirne D. Effects of acid adaptation on the survival of
Listeria monocytogenes on modified atmosphere packaged vegeta-
bles. International Journal of Food Science and Technology 2001:
36:477–487.