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REVIEW PAPER

Modified Atmosphere Storage of Grains Meats Fruits and Vegetables

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Consumer demand for more natural, minimally processed and fresh foods is increasing. Modified atmosphere storage is a well-proven technology for preserving natural quality of food products in addition to extending the storage life. Extensive research has been done in this research area around the globe for many decades. Modified atmosphere storage is one of the most successful preservation techniques suitable for wide varieties of agricultural and food products. Grain farmers are seeing advantage in using this method as strict regulations are enforced on the use of other chemical preservation methods. Success of modified atmosphere storage of grains depends on the airtightness of the grain bins and research is needed to find the techniques to improve the sealability of the existing grain bins. It is widely practiced in the meat industry for preserving primal and sub-primal cuts. Modified atmosphere packaging is also commercially successful for preserving certain fruits and vegetables. With the vast basic and fundamental knowledge available on this subject, the research in this area is taking a new dimension to suit the new consumer trends and demands. There are new interests in applying this technique to the consumer-ready products in the meat industry. This technique can be integrated with active or interactive packaging to improve the control over the package atmosphere to achieve superior product quality and safety. Time–temperature indicators on the packages to show the remaining storage life of the food product would improve food safety and inventory control. In this paper, published research on modified atmosphere storage specifically on grains, meats, fruits and vegetables is critically reviewed and opportunities for future research are explored. © 2002 Silsoe Research Institute. Published by Elsevier Science Ltd. All rights reserved

1. Introduction

Spoilage of food products is due to activity of insects or microorganisms or due to biochemical and physical changes in foods (Frazier & Westhoff, 1978). Various food preservation methods have been developed over the years. Traditionally, chemicals were used to control the activity of insects or microorganisms in food. An increased awareness by the environmental and health agencies and consumers of the harmful chemical residues in food and environment led to the restricted use of chemical preservatives in food (Calderon, 1980). Today, consumers demand more natural, minimally processed, fresh foods. During food preservation and processing, the colour, texture, flavour and nutritional qualities of the food undergo changes. There is always a compromise between food quality and safety.

Modified atmosphere storage is one of the food preservation methods that maintains the natural quality of food products in addition to extending the storage life. The storage life of food products is considerably extended by modifying the atmosphere surrounding the food, which reduces the respiration rate of food products and activity of insects or microorganisms in food. In the literature, the terms modified atmosphere (MA) and controlled atmosphere (CA) are used interchangeably. They both differ based on the degree of control exerted over the atmosphere composition. In MA storage, the gas composition is modified initially and it changes dynamically depending on the respiration rate of food product and permeability of film or storage structure surrounding the food product. In CA storage, the gas atmosphere is continuously controlled throughout the storage period. In most of the laboratory

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experiments, the effects of different atmosphere compositions on the storage life and quality of food products are evaluated. In such cases, the atmosphere composition is controlled continuously and hence the CA term is more frequently used. In this paper, the effects of MA or CA storage on grains, meats, fruits and vegetables are discussed. Research in these fields is reviewed and suggestions for future research are given.

2. Grains

Disinfestation of stored grain using MA involves the alteration of the natural storage gases such as carbon dioxide (CO_2), oxygen (O_2) and nitrogen (N_2), to render the atmosphere in the stores lethal to pests. The MA includes neither alteration of the storage atmosphere by addition of toxic gases such as phosphine or methyl bromide, nor regulation or alteration of the atmospheric water content. The MA may be achieved in several ways: by adding gaseous or solid CO_2, by adding a gas of low O_2 content (*e.g.* pure N_2 or output from a hydrocarbon burner) or by allowing metabolic processes within an airtight storage to remove O_2, usually with associated release of CO_2. Such atmospheres are referred to as 'high-CO_2', 'low-O_2', and 'hermetic storage' atmospheres, respectively. They are collectively known as 'modified atmospheres'(Banks & Fields, 1995).

Grains are usually dry and cannot support the growth of bacteria (Jay, 1992). Insects and moulds are major spoilage organisms in stored-grain ecosystems and are aerobic in nature. Therefore, creating an anoxic atmosphere in the stored-grain ecosystems has a lethal effect on insects and moulds and extends the storage life considerably. Carbon dioxide affects complex physiological processes in the insects (Nicolas & Sillans, 1989) and causes desiccation because spiracles remain open and water loss cannot be regulated (Jay *et al*., 1971).

Modified atmosphere storage of grains is a suitable alternative to the use of chemical fumigants and contact insecticides that are known to leave carcinogenic residues in the treated product (Bailey & Banks, 1980; Shejbal & de Boislambert, 1988). Stored grain insects develop resistance to the chemical fumigants (Bond, 1973; White & Loschiavo, 1985) as well as to modified atmospheric conditions (Navarro *et al*., 1985). The development of resistance, however, is less likely under modified gas atmosphere than with conventional fumigants (Krishnamurthy *et al*., 1986). The effectiveness of MAs in controlling insects is dependent on various abiotic (gaseous composition, relative humidity, temperature, length of exposure and gas pressure) and biotic (insect species, life stage and the size and distribution of infestation) factors. All these factors must be optimized to create an environment which is lethal to the insect species found in the stored grain. Researchers around the world have been conducting empirical studies to define atmospheric conditions for controlling various stored-grain insects. Both laboratory and field scale studies have been conducted to make MA storage of grains more effective and economical.

2.1. *Laboratory scale studies*

Harein and Press (1968) studied the mortality of adults and larvae of *Triboleum castaneum* (Herbst), and larvae of *Plodia interpunctella* (Hubner), when exposed to binary or ternary mixtures of atmospheric gases (CO_2, N_2 and O_2) at various temperatures (15·6, 26·7 and 37·8°C). As insects are the aerobic organisms, the mortality of insects increases with the decrease in O_2 concentration, increase in CO_2 concentration and increase in length of exposure (from 7 to 14 days). The insect mortality also increases with increase in temperature (15·6–37·8°C). An increase in temperature within the growth range increases the respiration rate and metabolic activities of insects and therefore unavailability of O_2 at high temperatures has a lethal effect on insects. Atmospheres containing $>36\%$ CO_2 were lethal to test insects even when O_2 was up to 15%. In the absence of CO_2, however, the O_2 concentration must be reduced to $<1\%$ to obtain lethal gaseous atmospheres. *Plodia interpunctella* larvae were more susceptible than *T. castaneum* adults or larvae under all test environments.

The importance of relative humidity in the control of stored product insects with MA was studied by Jay *et al*. (1971). The adults of *T. castaneum*, *T. confusum* and *Oryzaephilus surinamensis* (Linnaeus) were exposed to binary mixtures of O_2 and N_2 ($<1\%$ O_2: $>99\%$ N_2) and ternary mixtures of O_2, N_2 and CO_2 (9·8% O_2:30·5% N_2:59% CO_2 or 13·1% O_2:49·3% N_2 : 37·6% CO_2) at four different relative humidities (7–9%, 30–33%, 53–60% or 68–73%). The mortality of insects increased significantly with the decrease in relative humidity under all gas compositions.

Both inter- and intra-specific differences in mortality among the adults of *T. castaneum* , *T. confusum* and a Malathion-resistant strain of *T. castaneum* were observed under altered gas conditions when other variables like temperature, relative humidity and insect age were kept relatively constant (Jay & Pearman, 1971). Aliniazee (1971) investigated the effect of several binary gas mixtures containing CO_2, N_2 or He in combination with O_2 (2–20%) on the mortality of *T. castaneum* and *T. confusum*. The adults of both species were killed when

exposed to $<2\%$ O_2 in combination with N_2 or He for about 96 h. Carbon dioxide (80–98%) alone appeared to be responsible for mortality of insects when used in combination with O_2 concentration ranging from 2 to 20% as all combinations produced similar results. The data obtained by exposing mature and immature stages of both species to 100% CO_2 indicated that adults were the most susceptible followed by larvae, eggs and pupae. The insect mortalities increased with an increase in temperature (15·6–26·7°C) and a decrease in relative humidity. Under airtight conditions, the adults of *T. castaneum* were able to use the available O_2 more efficiently (O_2 concentration reduced from 20·9 to 1·7% in 7 days) than those of *T. confusum* (O_2 concentration reduced from 20·9 to 1·6% in 5 days) indicating differential respiration rates of these species.

In a study on the mortality of eggs and adults of *Cryptolestes ferrugineus*, Rameshbabu *et al.* (1991) used a portable CA unit capable of maintaining various levels of CO_2, O_2, N_2, relative humidity and temperature. After 96 h of exposure, maximum mortality for adults (99%) and eggs (85%) occurred at high CO_2 concentration (88–92%), low O_2 concentration (0–0·5%), high temperature (19·5–20·5°C) and low relative humidity (60–64%). In general, adults were more susceptible than eggs under high CO_2 and low O_2 atmospheres.

Various developmental stages of *Trogoderma granarium* (Everts) were subjected to CAs containing 60% CO_2 in air at 20 or 30°C and a relative humidity of 60% (Spratt *et al.*, 1985). Although the eggs, pupae and adults, all died within 6 days of exposure, some larvae survived even after 16 days under these conditions. Further exposure of larvae to 45, 60 and 75% CO_2 in air indicated that an exposure of >15 days to 75% CO_2 at 30°C is required for 100% mortality of larvae of this species.

2.2. *Large bin studies*

Jay *et al.* (1970) studied the mortality of Malathion-resistant *T. castaneum* adults under CAs containing about 35% CO_2 and 14% O_2. A concrete silo (9·1 m in diameter and 34·4 m high), reasonably sealed and fitted with inlets for gas introduction and distribution, gas sampling and insect introduction, was filled with 2203 m^3 of inshell Spanish peanuts. The mortality of insects in cages, placed 0·5–1·5 m below the surface, was 93·3% after 96 h of exposure to the MA as compared to only 9·2% in the normal atmosphere.

In another study, Jay and Pearman (1973) treated a silo containing 958·1 m^3 of shelled maize at 11–16% moisture content with CO_2 for the control of potential natural infestation by stored-product insects. During the test, the average composition of atmosphere was 61% CO_2, 8% O_2, and the rest, N_2 and other gases. The temperature ranged from 13·9 to 25·0°C and the relative humidity between 51 and 68%. The samples taken before treatment and held for 60 days contained an average of 144·4 live and 59·8 dead insects, and the samples taken after 96 h of treatment and held for 60 days contained an average of only 0·1 live and 1·1 dead insects. The majority of the insects in the untreated corn were *Sitophilus* spp. and *Sitotroga cerealella* (Olivier) but over 98% of those found in treated corn were *Sitophilus* spp.

Shejbal *et al.* (1973) studied the mortality of *Sitophilus granarius* (Linnaeus), *T. castaneum*, and *T. confusum* in hermetic silos treated with gaseous N_2 containing 0·1–1·0% O_2. The relative humidity ranged from 70 to 100% and the temperature was about 22°C during the experiment. Nearly 9 days of exposure to $<0·9\%$ O_2 was required to achieve complete mortality of adult insects. *Sitophilus granarius* was significantly more tolerant than either of the *Triboleum* spp.

Hoey (1981) reported on the use of CO_2 for the control of stored-grain insects in Australia. The gas was introduced at a slow rate at the bottom of vertical steel silos conforming to a satisfactory standard of gas tightness. After the initial purge at a rate of 1 t of CO_2 per 1000 t of grain, the gas was recirculated for at least 10 days. The treated silos were generally insect free for more than 4 months.

Annis (1981) studied the effectiveness of CO_2 fumigation of bag stacks of rice sealed in flexible polyvinyl chloride (PVC) enclosures. The gas was added until the gas leaving an exit vent at the top of the stack contained $>60\%$ CO_2, after that the stack was sealed. All of the insects (*S. oryzae*) placed in cages were killed. In another trial, the grain with a natural infestation of 15 live insects per kg of rice, mainly *Rhyzopertha dominica* (Fabricius) and *T. castaneum*, were subjected to similar gas treatment. No live insects were found in the bags opened 133 days after the treatment.

Steel tower silos containing shelled peanuts were treated with 63% CO_2 or 99% N_2 to study the mortality of *T. castaneum* and *Ephestia cautella* (Walker) (Jay, 1983). The average temperature was 27°C and the relative humidity 66%. The larvae of both species were more tolerant to 63% CO_2 than any other life stage. The larvae of *E. cautella* were more tolerant to 99% N_2 than pupae but the reverse was true for *T. castaneum*.

To develop a practical method to kill insects using MAs, Alagusundaram *et al.* (1995a) conducted experiments in three 5·56-m-diameter bolted-metal bins. The bins were constructed from corrugated, galvanized steel sections. One bin was equipped with a 0·46 m diameter and 4·7 m long circular duct on its floor. The duct had

perforations for a length of 3·3 m from the inner end. The second bin had a fully perforated floor and the third bin had a solid concrete floor. Five different methods of introducing CO_2 as dry ice in the grain mass were evaluated for their ability to create and maintain uniform CO_2 concentrations within the interstitial space. The uniformity of the CO_2 distribution was determined by measuring CO_2 concentrations at 39–52 locations in the grain mass and maintenance of CO_2 was determined by measuring CO_2 concentrations for up to 15 days. The methods evaluated were: (i) introduction of dry ice under the perforated floor or in the perforated duct, (ii) introduction of dry ice on the top surface of the grain covered with a CO_2-impermeable sheet, (iii) introduction of equal amounts of dry ice on the top surface under the sheet and in the perforated duct, (iv) introduction of dry ice through a 10-cm-diameter perforated tube installed vertically in the centre of the grain bulk and (v) introduction of one-quarter of the dry ice on the top surface under the sheet and the remaining three-quarters in an insulated box placed under the sheet. The fourth method gave the most uniform CO_2 concentration in the grain mass and used the least amount of CO_2 to maintain the desired CO_2 concentration for the required exposure period of 15 days. Normally infestations are detected in bins that are full of grain. Installation of a 10-cm-diameter perforated tube in such a bin would be very difficult, therefore the fifth method was recommended for practical use. For all five methods of introducing CO_2 in the grain mass, the CO_2 concentration was greater in the bottom portion of the bin than in the top portion of the bin filled to a depth of 2·5 m (Alagusundaram *et al*., 1995a).

The mortality of caged adult rusty grain beetles under elevated CO_2 concentrations was determined at 39 locations in each of the 5·56-m-diameter bins (Alagusundaram *et al*., 1995b). The bins were filled with wheat to a depth of 2·5 m. Two different modes of application of dry ice to create high CO_2 concentrations in the wheat bulks were evaluated: (i) pellets on the grain surface and in the aeration duct and (ii) pellets on the grain surface and blocks in insulated boxes on the grain surface. In the first mode of application, dry ice sublimed quickly and had to be replenished frequently. Introducing dry ice in insulated styrofoam boxes was less labour intensive and more economical. At 0·55 m above the floor, the mortality of rusty grain beetle adults was more than 90% while in the top portions of the bulk (2·05 m above the floor) the mortality was only 30%. On average, about two-thirds of the insects placed in the bin were killed.

The mortality of insects is usually measured at constant CO_2 concentrations for fixed exposures under laboratory conditions. However, in real-life situation, the concentration of CO_2 in a grain bin decreases due to leakages. Mann *et al*. (1999a, 1999b) developed a regression equation for predicting mortality of *C. ferrugineus* for different CO_2 concentrations at 25°C using published data. The developed equation was then used to calculate lethality at daily intervals, using an average CO_2 concentration over the daily interval. Cumulative lethality index (CLI) was calculated by summation of ratio of the interval length to the lethal exposure time, calculated by the developed regression equation, over all intervals. When CLI is equal or greater than one, complete mortality should occur. Out of six experimental fumigations conducted in sealed welded-steel hopper bins for validation of this technique, good agreement between the observed insect mortality and predicted CLI was reported in five experiments. In the sixth experiment, the CLI over predicted the insect mortality. It is worthwhile to note that this technique is valid only at the temperature of 25°C.

2.3. *Mathematical modelling*

A mathematical model of diffusion of CO_2 in stored wheat was solved using the finite element method for a three-dimensional configuration (Alagusundaram *et al*., 1996a). The model was validated using data from pilot bins and requires further improvements and validation using data from full-size bin experiments. Initially, the deviations between the predicted and measured CO_2 concentrations were high. As an example, for the bin with open top surface, the mean relative errors were 71% at 3 h and 31% at 21 h. Similar results were obtained for the seven other cases studied. The model was modified by incorporating an apparent flow coefficient during the sublimation period of the CO_2 (Alagusundaram *et al*., 1996b) and the diffusion coefficient afterwards. With this modification, the errors in the above example were reduced to about 21% at 3 h and 12% at 21 h (Alagusundaram *et al*., 1996a). The main problem in this modified model was that the apparent flow coefficient has to be determined experimentally. Therefore, a third model was developed by solving the combined convective–diffusive equation (hereafter referred to as the combined model) for transport of CO_2 within the bulk grain (Alagusundaram *et al*., 1996c). The errors based on the combined model for the above example were 24% at 3 h and 16% at 21 h. Although the errors were slightly greater for the combined model than the apparent flow model, the combined model does not require the measurement of a bin-specific coefficient. Therefore, the combined model can be used to predict the distribution of CO_2 in bulk

grain and thus in designing and operating insect control strategies. Errors of this order of magnitude are expected when dealing with biological systems and do not reduce the usefulness of the mathematical model for developing design strategies. As an example, 40% CO_2 concentration will kill *Cryptolestes ferrugineus* (Stephens) in stored wheat at 25°C. A 16% error at this concentration level means that the predicted concentration will be within $\pm 3{\cdot}2$ percentage points. The mortality of insects is a cumulative phenomenon and is linearly related to the product of CO_2 concentration and time (Alagusundaram *et al.*, 1995b). The predicted mortality would have some error but still can be used as a guideline. The combined mathematical model can predict the CO_2 concentrations at any point in a grain bulk stored in a bin of any shape and size. It can be used by designers to determine the best location for adding CO_2, the approximate amount of CO_2 needed, and the expected level of insect mortality.

2.4. *Development of tolerance to modified atmospheres*

Navarro *et al.* (1985) reported on the development of resistance to CO_2-rich atmosphere among the adults of *S. oryzae*. Two groups of insects were exposed to 40% CO_2 in air for seven successive generations, or to 75% CO_2 in air for ten successive generations at 26°C and 100% relative humidity. The generations of insects subjected to selection pressure were compared with those of control for their tolerance factor (LT_{95} selected generation/LT_{95} non-selected generation; where LT_{95} refers to the lethality time in h for 95% mortality). The results indicated that *S. oryzae* has the genetic potential to develop resistance to CO_2-rich atmosphere. The tolerance factor at the seventh generation (under 40% CO_2), and tenth generation (under 75% CO_2) was 2·15 and 3·34, respectively. Reduction of relative humidity to 60% and augmentation of O_2 concentration to 21% at these CO_2 levels did not markedly alter the tolerance factor indicating that the tolerance in these insects was largely due to the action of CO_2. Removal of selection pressure for five generations in the case of 40% CO_2 group and for four generations in the case of 75% CO_2 group resulted in significant reduction in their tolerance to the CO_2-rich atmosphere indicating that the strains obtained were not completely isogenic. While resistance can occur to some extent, it is unlikely that successive generations of isolated populations would be exposed to CO_2.

2.5. *Effect of modified atmospheres on grain quality*

Shejbal *et al.* (1973) monitored several attributes related to grain quality (gluten %, maltose %, turbidity index, ash % and alveogram) in soft wheat stored for up to 78 weeks under anaerobic conditions. No detrimental effect on these characteristics was found due to storage conditions. In addition, the mould count was significantly lower even in high-moisture grain stored under N_2 as compared to that stored in air. Banks (1981) presented an extensive review of several studies related to the effect of CA storage on grain quality. Most of the studies supported the use of either $<1\%$ O_2 in N_2 or $>60\%$ CO_2 in air for the preservation of cereal grain quality. This is true especially if it is necessary to maintain a high level of germination as in malting barley or where high-temperature or high-moisture contents make the storage in air prone to mould growth. In general, the CA storage preserved grain viability, prevented mould growth, had no detrimental effect on milling and baking characteristics of wheat, better preserved the malting properties of barley, and did not adversely affect the chemical composition of stored grain.

2.6. *Commercial use of modified atmospheres*

Australians use MAs the most for grain treatment. Most of the farm bins in Australia are now constructed airtight (rolled steel) with pressure relief valves for CO_2 fumigation. Currently, bins with MA capability are installed in grain elevators operated in Vancouver, Canada. The successful implementation of MA in grain storage largely depends on the ready availability of CO_2 and construction of airtight structures. The most feasible structure present on farms or at primary elevators is a welded steel hopper bin that can be retrofitted with appropriate seals, pressure relief valve, and recirculation pump for MA storage of grains (Mann *et al.*, 1999c).

2.7. *Benefits and limitations*

In addition to providing an effective control of pests, the MA storage prevents mould growth, preserves grain quality and maintains high level of germination in the stored grain (Banks, 1981). In spite of these benefits, however, this technique has its own limitations. The major limitation appears to be the high initial cost of airtight storage structures and sealing the existing structures to the desired airtightness (Annis, 1987; Jay, 1983). There may be an added cost of gas transportation unless a gas generation facility could be built on-site but at a substantial initial expense and technical expertise. The adsorption of CO_2 by concrete (Banks & Macabe, 1988) may result in structural damage to the concrete silos due to pressure changes and chemical reactions.

In view of the global concerns about the use of chemicals, MA storage is considered to be an effective alternative as its benefits appear to outweigh the limitations. Under current practical conditions, complete mortality by CA storage alone is difficult to achieve and therefore the mortality obtained by the CO_2 treatment can be one component of an integrated pest management (IPM) strategy that does not require the application of chemical insecticides. Under Canadian conditions, if a CO_2 treatment is applied in summer when grain temperatures are high (20–30°C), about 70% reduction in insect population can be obtained. The surviving adults which have been exposed to 7–8% CO_2 produce 60% fewer offspring than untreated adults (White *et al*., 1995). Also the *C. ferrugineus* adults move to the bottom and are attracted to high CO_2 concentrations (White *et al*., 1993). Both of these phenomena should assist in decreasing the insect population until winter when cold temperatures, which are often not effective alone for this cold-hardy insect, can be used to further reduce or eliminate the insect populations. Aeration with cold air during winter months accompanied by mechanical control of insects by stirring the grains in the bin in conjunction with MA storage during summer months would be a good IPM strategy.

3. Meats

Extensive research on basic studies such as effect of modified atmosphere packaging (MAP) of meat on microorgansims and storage life of meat has been conducted since early 1920s. Due to poor technological state of instrumentation and polymer technology, the packages that were reported as impermeable on many earlier MAP studies were, in fact, permeable to small amounts of various gases. Contradictory results were reported in earlier studies and therefore only the studies after late 1970s were reviewed in this paper.

Developments in polymer technology have made the modified atmosphere packaging (MAP) of meat commercially successful. Today, the packaging films are available with different gas permeabilities to suit various needs for different types of MAP. The effect of MA on the storage of meat is considerably different to that on the storage of grains. Meat contains an abundance of nutrients and water in available form and can support all kinds of microorganisms such as bacteria, yeast and mould and therefore is a highly perishable product (Jay, 1992). Bacteria are the dominant spoilage organisms. Unlike insects and moulds, there are certain groups of bacteria that can grow under anoxic atmospheres. In addition, the availability of O_2 surrounding the meat determines the colour of the meat, which is of utmost economic importance. Therefore, the underlying concepts behind meat colour are first discussed and then various MAs and packaging techniques are explained.

3.1. *Meat colour*

Consumers relate the red colour of meat to its freshness and attribute brown colour of the meat to bacterial spoilage or meat from mature animals. Colour deterioration is the major factor limiting the marketability of fresh red meats (Shay & Egan, 1987). Myoglobin is a muscle pigment responsible for the meat colour. It is commonly found in three forms; namely oxymyoglobin, deoxymyoglobin and metmyoglobin. The relative proportions of these three forms of myoglobin determine the colour of fresh meat. When the animal is alive, the major proportion of myoglobin is in the oxygenated form. Oxymyoglobin is bright red in colour and is desirable in fresh meats. When O_2 is not available, myoglobin is in the deoxygenated form, which is purple (Seideman *et al*., 1984). The conversion of oxymyoglobin to deoxymyoglobin is a reversible reaction. Conditions such as low O_2 tension especially in the range of 1–20 mm of Hg partial pressures, high temperature, ultra-violet rays and exposure to atmospheric O_2 for long periods of time cause the formation of brown metmyoglobin (Seideman *et al*., 1984). Metmyoglobin is the major pigment responsible for discolouration of meat.

3.2. *Modified atmosphere gases*

Various MAP systems have been developed and investigated for increasing the shelf life of fresh meat (Buys *et al*., 1993; Shay & Egan, 1990). Common gases used in MA are CO_2, O_2 and N_2. Carbon dioxide is bacteriostatic. Sometimes, O_2 is included in the MA gas mixture to retain the red colour of meat. Nitrogen is an inert gas; it does not possess any bacteriostatic effect. It is used as a filler gas in the MA gas mixture. The inhibitory effect of CO_2 increases with a decrease in meat temperature (Jay, 1992), which is contrary to the inhibitory effect of CO_2 in grains. This is due to the difference in effect of CO_2 on insects compared to that on microorganisms. The insects are aerobic and their respiration rate increases with an increase in temperature and therefore the lethal effect is higher at higher temperatures. Anaerobic bacteria are resistant to high concentrations of CO_2. As the temperature decreases, the solubility of CO_2 increases and carbonic acid is formed and there is slight drop in pH in meat (Farber, 1991). Therefore, the inhibitory effect of CO_2 increases with a decrease in meat temperature. As CO_2 is water

and lipid soluble, it is accumulated in lipid bilayer of the microbial cell membrane and affects the cell permeability leading to intracellular pH changes. It is also known to affect the functionality of enzymes and proteins, thereby blocking the metabolic activities (Farber, 1991). When the meat is stored under CO_2, there is a shift from natural aerobic microflora to anaerobic bacteria dominated by lactic acid bacteria (LAB). Lactic acid bacteria are capable of continuously pumping out CO_2 from the cell to its environment, thereby maintaining its metabolism. As LAB spend a lot of energy in pumping out CO_2 from the cell, their growth rate is very slow. Lactic acid bacteria are also known to produce antagonistic substances and cause a slight drop in pH, creating an unfavourable environment for most pathogens and Gram-negative bacteria (Jay, 1992). Therefore, by introducing or encouraging the formation of an atmosphere containing CO_2 in the absence of O_2, the shelf life of meat can be greatly increased (Holley *et al*., 1993). Shelf life of meat has been extended up to 15 times that attained in air (Gill & Penny, 1988; Holley *et al*., 1994). Meat tenderness is also improved during this extended storage life (Taylor, 1985).

3.3. *High carbon dioxide modified atmosphere packaging*

There are two different methods used to obtain CO_2-enriched atmospheres. The first method, called vacuum packaging, has been stated as the greatest innovation in meat handling in the last 20 years (Taylor, 1985). It involves drawing a vacuum within the meat package and sealing it. The respiration of bacteria and meat tissue quickly consume the residual O_2, releasing CO_2. Concentrations of O_2 are reduced from 21% to less than 1%, while CO_2 concentrations increase from less than 1% to 10–40% (Holley *et al*., 1993). Today, vacuum packaging is the most commonly used technique in the North American meat industry for transporting primal and sub-primal cuts to the retail stores. The second method of obtaining a CO_2-enriched environment involves evacuating air out of the package and back flushing it with CO_2. This packaging option is more expensive than vacuum packaging, but can offer improved storage life.

3.4. *Microbiology of meat stored under 100% carbon dioxide*

Various gas mixtures have been tried. Spahl *et al*. (1981) reported that the most effective gas environment from the point of view of sensory acceptability was 100% CO_2. Blickstad and Molin (1983) reported that the storage of lean pork in 100% CO_2 at 0°C gave a storage life of about 3 months. Storage temperature is the most important extrinsic factor affecting the storage life of fresh meat. The maximum potential storage life of fresh meat can be achieved when the product is held at the lowest possible temperature without freezing (−1·5°C). In this section, the microbiology of meat stored under 100% CO_2 at −1·5°C is given.

3.4.1. *Spoilage microorganisms*

Storage of meat in CO_2 atmospheres at low temperatures inhibits the aerobic, putrefactive bacteria and extends storage life considerably. The full bacteriostatic effects of CO_2 are achieved when the gas is added to the packs in sufficient quantity to fully saturate the meat and maintain a head space of excess CO_2 at atmospheric pressure (Gill & Penney, 1988). This quantity of CO_2 is between 1 and $2\,l\,kg^{-1}$ of meat (Jeremiah *et al*., 1996) . Penney and Bell (1993) demonstrated that CO_2 was completely absorbed by meat gassed with CO_2 at $1\,l\,kg^{-1}$ of meat, while packs gassed at $2\,l\,kg^{-1}$ of meat retained a residual CO_2 of approximately 0·5 *l*. Storage of meat in high CO_2 atmospheres selects for the growth of psychrotrophic LAB (*Lactobacillus* and *Leuconostoc*), *Carnobacterium* and *Brochothrix thermosphacta*. The latter produces organoleptically offensive byproducts and can cause early spoilage of meat under anoxic conditions (Gill & Harrison, 1989). If an anoxic 100% CO_2 atmosphere is maintained without any trace of O_2, LAB dominate *B. thermosphacta* (McMullen & Stiles, 1991). Gill and Harrison (1989) reported that *B. thermosphacta* was the dominant bacteria on the surface of retail-ready pork stored under CO_2 atmospheres at 3°C. At −1·5°C, however, *B. thermosphacta* was totally inhibited by CO_2 and the dominant organisms were LAB. As *B. thermosphacta* is sensitive to undissociated lactic acid and low pH under anaerobic conditions, LAB dominate over *B. thermosphacta* in meat at low temperatures (Grau, 1980).

Some non-aciduric lactobacilli were reclassified and moved to a new genus, *Carnobacterium* (Collins *et al*., 1987). They are similar to LAB, producing predominantly lactic acid from glucose, and are found in vacuum-packaged meat and related products at low temperatures. Their rate of growth is higher than LAB at low temperatures and therefore they initially dominate in fresh meat packaged under anoxic atmospheres. They differ from LAB in that they cannot grow on acetate agar or broth and cannot tolerate low pH (Collins *et al*., 1987). Following the initial dominant growth of carnobacteria for 4–6 weeks, they are suppressed by production of lactic acid and a slight drop in pH of meat, and LAB become the dominant microflora. Lactic acid bacteria reach maximum num-

bers after 6–9 weeks of storage and the products become unacceptable organoleptically (Jeremiah & Gibson, 1997). Thus, the microflora of chilled meat under anoxic atmospheres is dominated first by carnobacteria and then by LAB throughout the storage period. This reduces the threat from pathogens and promotes food safety.

When pork chops are transferred from CO_2 to air, LAB initially dominate the aerobic microflora, but pseudomonads emerge as the second most dominant group (Greer *et al*., 1993). A sufficient amount of CO_2 binds to proteins such as haemoglobin which accounts for the residual effect. The binding of CO_2 to free amino groups is reversible but the process is relatively slow at low temperatures (Jones, 1989).

3.4.2. *Pathogens*

Potential pathogens in meat stored under anaerobic conditions and at low temperatures capable of growth are *Yersinia enterocolitica, Listeria monocytogenes* and *Aeromonas hydrophila*. Enfors *et al*. (1979) reported that *Yersinia* and *Aeromonas* spp. are found on vacuum, N_2 atmosphere and low CO_2 atmosphere packaged meat. When 100% CO_2 and a storage temperature of $-1{\cdot}5^{\circ}C$ are simultaneously applied (hurdle concept), none of the above pathogens are able to grow and compete with the dominating LAB (Farber, 1991; Enfors *et al*., 1979). Buchanan and Klawitter (1992) reported that *Carnobacterium piscicola* suppress and outgrow *Listeria monocytogenes* in various refrigerated foods. Therefore, health hazards would not be expected as long as 100% CO_2 and $-1{\cdot}5^{\circ}C$ are stringently maintained and controlled.

3.5. *Centralized packaging*

The current meat distribution system involves the transportation of primal and sub-primal cuts in vacuum packages to retail stores, where the cuts are fabricated into retail-ready products packaged in O_2 permeable films. There is a growing interest in centralized preparation of retail-ready meat cuts and then distribute them to widely dispersed retail stores due to convenience of high-quality 'ready-to-go' products consistently provided to consumers at lower costs (Jeyamkondan *et al.,* 2000). Moving the packaging of retail-ready cuts from retail stores to the packer level or centralized packaging centre eliminates time-consuming labour of cutting, trimming and overwrapping the meat at retail stores. A centralized packaging centre can support specialized machinery such as robotics which minimize human handling, thereby greatly improving food safety and quality. Higher efficiency can be achieved at the centralized location, due to the greater mass of production (Scholtz *et al*., 1992). Only the saleable meat cut is transported from the centralized packaging centre to the retail store; fat trimmings, bones and other wastes remain at the centralized packaging centre eliminating unnecessary refrigerated transport to retail stores. Developments in polymer technology made centralized packaging a reality in the meat distribution system and different centralized packaging techniques are discussed below.

3.5.1. *High-oxygen modified atmosphere packaging system*

This type of packaging system is known to meat industry for many decades. As metmyoglobin is formed at low O_2 tensions, O_2 concentration in the gas mixture is usually higher than that in air (Shay & Egan, 1987). Therefore, the colour of the meat is bright red throughout the storage period. Aerobic bacteria tolerate high concentrations of O_2 and their growth rate can be reduced by including CO_2 in the gas mixture (Gill & Molin, 1991). Work by Gill and Jones (1994) indicates that high-O_2 MAP systems extend the storage life of beef by 2 weeks while maintaining acceptable red colour at $-1{\cdot}5^{\circ}C$. Large supermarket chains can prepare the retail cuts at a centralized location and can provide them at superior quality consistently to all of its stores. For instance, a giant (500 store) British supermarket chain, Tesco, has converted its entire fresh meat operation to centralized packaging of high-O_2 MAP retail-ready packs and reported commercial success (Brody, 1996). A 300 store, Marks & Spencer, British supermarket chain introduced *St Michael* fresh meat cuts combining vacuum skin packaging (VSP) and high-O_2 MAP (Anonymous, 1989). Individual retail-ready meat cut is first vacuum skin packaged in an O_2-permeable film and is then bagged in an impermeable Nylon pouch with a gas mixture of 80% O_2 and 20% CO_2. High-O_2 MAP system is commercially viable for distribution of retail-ready meats to local markets. However, the extension in storage life is not enough for transporting meat to distant markets. Also the cost of individual MA retail packs is high, when production rates are low.

3.5.2. *Cryovac peeling*

Cryovac (Sealed Air Corporation, Duncan, SC) has developed Darfresh® peelable VSP for retail-ready meat cuts. Retail-ready cut is first vacuum skin packaged in a transparent O_2-permeable film, which is then again vacuum skin packaged in a transparent O_2-impermeable film. Just before the retail cut is displayed in retail-display case, the outer impermeable film is removed and meat blooms on exposure to air. A similar technique is applied to retail-ready cuts in foam trays. The retail cut

is first placed in a barrier foam tray, wrapped with a transparent O_2-permeable film, and is again over-wrapped with a transparent O_2-impermeable film. At the retail store, the outer impermeable layer is manually removed to cause blooming of meat before retail display (Brody, 1996). Studies on storage life of these cuts are not available.

3.5.3. *Flavaloc fresh*

Garwood Packaging, Inc., Indianapolis, has developed a modified atmosphere, retail-ready, meat packaging system known as Flavaloc^{TM} Fresh with assistance from CSIRO, Australia. ACI Plastics Packaging Solutions (ACI Operations Pty Ltd., Australia) is marketing this new centralized packaging system in Australia and New Zealand. The Flavaloc Fresh package has three parts—a shallow, white base tray made of polyethylene terephthalate (PET) plastic *Estapac* PET 9921 in which retail cut is placed, a transparent polyvinyl chloride (PVC) O_2-permeable film stretched across the meat product and a transparent O_2 impermeable lid called 'dome', made of *Easter* PETG 6763 polyester (Eastman Chemical Company, Kingsport, TN). Retail cuts are prepared at a centralized packaging centre and are placed in the preformed trays, together with pads to absorb drip losses. Air is then evacuated and back-flushed with a gas mixture (at atmospheric pressure) containing at least 30% CO_2 and remaining N_2, with less than 300 p.p.m. of residual O_2 (Zhao *et al.*, 1994). Patented single chamber technology then seals the tray with the PVC membrane and the dome. The colour of the meat is purple with the dome in place. The company's literature claims that this new system gives a storage life of about 21–40 days in the dome and subsequent 4 days of retail-display life. Once it reaches the retail store, the dome is removed and the meat blooms within 20 min.The package is attractive and appealing to consumers, when compared to conventional packs. Commercial success was reported in the export trials of Flavaloc Fresh from Australia to Hong Kong.

3.5.4. *Windjammer case-ready packaging system*

Retails cuts are first individually packed in modified atmosphere packages to give a storage life up to 21 days (Zhao *et al.,* 1994). Before retail display, a gas exchange machine evacuates the anoxic atmosphere in the retail pack and back-flush with high-O_2 MA containing 80% O_2 and 20% CO_2 to cause blooming of meat. This system is also known as 'dynamic gas exchange system'.

3.5.5. *Master packaging*

In this technique, 4–6 conventional retail packs (*i.e.* over-wrapped in O_2-permeable films) are placed within a large pouch which is usually made of a metalized (aluminium) laminate with no measurable O_2 transmission, known as a 'mother bag' (Gill & Jones, 1994). The laminate pouch is then evacuated to remove O_2 and back-flushed with a desired gas mixture. The most effective gas composition with respect to extending storage life and sensory characteristics is saturating (100%) CO_2 (Spahl *et al.*, 1981). Holes are burned in at least two locations on the O_2-permeable films of the retail packs so that meat comes into contact with the MA rapidly. The packaging cost is less than that of individual MA packs (Shay & Egan, 1987). In response to consumer demand, master packs are individually opened and the retail cuts are placed in the retail-display case. Within 30 min of exposure to atmospheric O_2, the meat blooms to a desirable red colour (Penny & Bell, 1993).

Master packaging basically differs from other systems in that 4–6 retail packs are grouped together in a mother bag rather than a single retail cut and therefore is more economical. It also differs from Flavaloc Fresh system in that it uses opaque aluminium laminate film as the outer cover compared to attractive transparent dome in the latter system. The O_2 transmission rate of the aluminium laminate film is almost zero, thereby reducing the formation of metmyoglobin. The aluminium laminate film is opaque; however, it is removed by retail personnel before the retail cuts are displayed. Master packaging differs from Windjammer case-ready packaging system in that it relies on atmospheric air to bloom the product. This eliminates the need for an expensive gas exchange machines at retail stores. Therefore, master packaging is more economical.

Scholtz *et al.* (1992) studied the influence of different centralized packaging systems (PVC over-wrap, modified atmosphere packaging of individual retail packs, vacuum skin packaging and the mother bag concept or master packaging) on the storage life of fresh pork at 0°C. Master packaging was the most promising with regard to storage life (21 days master pack storage with a subsequent retail case life of 4 days) followed in order by individual modified atmosphere packaging (14 days), vacuum skin packaging (7 days), and PVC over-wrap (4 days). Holley *et al.* (1993) studied the storage life of master packaged pork. Pork under 100% CO_2 atmospheres at 4°C had a storage life of 2 weeks with a subsequent 6-day aerobic storage life.

Gill and Jones (1994) studied the storage life of master packaged beef steaks under various atmospheres at –1·5°C. Steaks stored under 100% CO_2 or 100% N_2 for less than 4 days were only slightly desirable because of the formation of metmyoglobin on the surface due to the presence of small amounts of residual O_2 in packages. Within 4 days of storage, metmyoglobin was

converted to myoglobin by muscle tissue enzymes (reductases) and the meat had a desirable appearance. Master packaging under a CO_2+O_2 (1:2 v/v) atmosphere gave an acceptable appearance initially but the colour began to deteriorate after 12 days of storage. Therefore, they concluded that a CO_2+O_2 atmosphere is appropriate for storing meats that are intended for markets having a distribution time of less than 4 days. Master packaging in 100% N_2 gives a storage life of 4 weeks and 2 days of subsequent retail display, while master packaging in 100% CO_2 gives about 7 weeks of storage life in the master pack and 2 days of subsequent retail display. After 7 weeks of storage in 100% CO_2, LAB produce slight acidic odours. Meat also loses its colour stability beyond 7 weeks. They clearly warned that this storage life can be obtained only with products of high microbiological quality.

3.6. *Active packaging*

Traditionally packaging materials are designed in such a way that the interaction between the packaging material and food is eliminated or at least minimized. Modern packaging techniques utilize the interactions between the packaging material and food in a desirable way (Labuza & Breene, 1989). As headspace composition dynamically changes during storage and distribution period, it must be controlled continuously to achieve superior food quality and safety. These packaging techniques are known as 'active packaging' or 'smart packaging' or 'intelligent packaging'. One of the active packaging concepts is the O_2 scavenging system. Labuza and Breene (1989) extensively reviewed the O_2 scavenging technology and described the various patents available in this area. Floros *et al.* (1997) described the recent patents in this technology. Other reviews available in this area are Ahvenainen and Hurme (1997), Rooney (1995) and Labuza (1990).

The Japanese are the forerunners of O_2 scavenging technology. Ageless® (Mitsubishi Gas Chemical Co. Inc., Tokyo, Japan) O_2 scavenging sachets are used in food industries around the world. The ferrous iron powder is sealed in a moisture and gas-permeable package, which is labelled 'Do not eat'. The ferrous iron absorbs O_2 present in the package headspace and is oxidized to ferric state. Most of the iron-based O_2 scavengers requires moisture as an activating agent. Ageless sachets are commercially successful for various food products; however, the kinetics of this scavenging system at very low O_2 concentrations (300–600 p.p.m.) at low temperature ($-1{\cdot}5^\circ C$) is not known. There might be consumer resistance for placing the packaging inside the meat package.

Gill and McGinnis (1995) used FreshPax™ 200R (Multisorb Technologies, Inc., Buffalo, NY) a commercially available iron-based O_2 scavenger in a sachet to prevent surface discolouration. FreshPax™ 200R is composed of activated iron-oxide powder mixed with acids, salts and humectants to promote oxidation of iron. Oxidation of the iron compound removes O_2 from the package atmosphere and prevents surface discolouration. The same authors reported that O_2 concentration in the pack atmosphere must be reduced to below 10 p.p.m. within 30 min at $2^\circ C$ or within 2 h at $-1{\cdot}5^\circ C$ for blooming of ground beef.

Multisorb Technologies, Inc. (Buffalo, NY) introduced FreshMax® O_2 absorbing labels which can be stuck to the package and are suitable when the O_2 absorbing requirements are less than 50 m*l*. The labels, in which custom printing can be done, have flat, flexible and thin profile, and can be adhesive backed, making them less visible to consumers unlike the O_2 scavenging sachets. These pressure-sensitive labels, in which iron powder is imbedded in a matrix, can be applied to the package by high-speed labelling equipment.

Sealed Air Corporation (Saddle Brook, NJ) introduced a new O_2 scavenging film Cryovac® OS1000, a multilayer flexible film with a coextruded sealant. The proprietary O_2 scavenging polymer is incorporated within the sealant and therefore invisible to consumers unlike the sachets and labels. The O_2 scavenging polymer is dormant, until it is activated by an ultraviolet (UV) light system (Cryovac® Model 4100 UV triggering unit, Sealed Air Corporation, Saddle Brook, NJ) just before packaging. It does not require moisture as an activating agent for scavenging and therefore the product is unaffected. The company's literature claims that this O_2 scavenging technology reduces the O_2 levels in a MA package (which is usually in the range of 0·5–1%) to few p.p.m. in 4–10 days.

Recently, Tewari *et al.* (2001, 2002a, 2002b) studied the storage life of master packaged beef tenderloins (*psoas major*, PM) and pork loins (*longissimus dorsi*, LD) in integration with other technologies such as O_2 scavenging system, CAPTECH process (a process capable of creating a CO_2 atmosphere in the package with less than 300 p.p.m. of residual O_2), and liquid N_2 refrigeration system. To maintain meat at $-1{\cdot}5\pm0{\cdot}5^\circ C$, Tewari *et al.* (2001, 2002a, 2002b) used the portable, shipping, jacketed container (capacity: 200–300 kg of retail cuts of meat), refrigerated with liquid N_2, designed and developed by Jeyamkondan *et al.* (2001). Results of Tewari *et al.* (2001, 2002a, 2002b) showed that O_2 scavenging sachets (Ageless® FX-100, Mitsubishi Gas Chemical Co. Inc., Tokyo, Japan) must be placed inside the retail packs rather than in the mother bag. Eight sachets were placed below the absorption pads in the

retail cuts. The meat cuts were then examined at regular intervals for visual, odour, taste and microbial characteristics and storage life of the meat cuts were determined. The initial O_2 concentration was less than 100 p.p.m. after packaging and was reduced to 0 p.p.m. in 3 days and was maintained throughout the storage period. This study demonstrated that the storage life of beef and pork cuts (under 100% N_2) of 9–10 weeks in master package followed by 3 days of retail display life, can be achieved. In contrast, Gill and Jones (1994) reported the master packaging of beef steaks in 100% N_2 gave a storage life of 4 weeks and 2 days of subsequent retail display. The longer storage life achieved in the former study was attributed to the presence of O_2 scavenging system and strict temperature control.

4. Fruits and vegetables

Fruits and vegetables continue to respire even after harvest. The respiration rate of fruits and vegetables is much higher than that of grains and meats. Enzymes are active and the food reserves in the fruits and vegetables are utilized for metabolic activities. The products begin to ripen and ethylene is produced as a byproduct of the ripening process. The ethylene, in turn, accelerates the ripening process. During the ripening process, the climacteric fruits improve in quality initially, but begin to degrade quickly. These metabolic and biochemical process can be manipulated by changing the environmental conditions. Oxygen is required for many metabolic activities and therefore reducing the O_2 level surrounding the product reduces the overall metabolic activities and preserves food reserves. However, reducing the O_2 level beyond a limit initiates the anaerobic glycolysis and off-flavours are produced (Labuza & Breene, 1989). Fruits and vegetables are more sensitive to environmental conditions than grains and meat. Traditionally, chilling is used to preserve fruits and vegetables. Today, MA storage is used as a supplement in conjunction with low-temperature preservation to extend the storage life of fruits and vegetables. The specific environmental conditions vary widely, not only between the different types and cultivars of fruits and vegetables but also within the same cultivar grown in different seasons or locations. In general, storage conditions include:

(1) the lowest O_2 level to reduce the respiration rate and ripening or senescence but safe enough to prevent low O_2 injury,
(2) the highest safe CO_2 level to attenuate the respiration rate and ripening and to prevent high CO_2 injury,
(3) the highest relative humidity (r.h.) levels to reduce moisture loss and preserve freshness,
(4) the lowest temperature to reduce respiration rate but safe enough to prevent chilling injury, and
(5) lowest ethylene levels to suppress ripening (Dilley, 1990).

4.1. *Physiological and biochemical effects of modified atmospheres*

The respiration rate is considerably reduced by high CO_2 and low O_2 storage. Low respiration rate reduces the overall metabolic and biochemical activities (ethylene production, rapid acid catabolism, changes of pectic substances in the cell wall leading to softening, *etc.*) in the cell, thereby reducing the rate of utilization of food reserves. By reducing the respiration rates, MA also lowers the heat production due to respiration.

Carbon dioxide has an antagonistic effect on enzymes involved in ethylene biosynthesis. As O_2 is required in the production of ethylene, low O_2 storage suppresses the ethylene production. During MA storage, a compound precursor to ethylene is accumulated in the products. Therefore, when the products are transferred to air, ethylene is rapidly produced and the products ripen faster (Wang, 1990). Modified atmospheres delays the onset of ripening process and increases the firmness in fruits. By inhibiting an enzyme polyphenol oxidase in lettuce, mushrooms and snap beans, MA prevents browning of these tissues (Wang, 1990).

When O_2 is not available, fruits and vegetables degrade glucose anaerobically by glycolysis to generate energy. In the glycolysis pathway, aldehydes, alcohols and lactates are produced. Accumulation of these anaerobic byproducts produces off-flavours associated with physiological disorders, leading to an unacceptable eating quality. Therefore, low levels of O_2 (2% in sweet potatoes) must be included in the MA gas mixture to prevent anaerobic respiration (Wang, 1990).

4.2. *Low-ethylene storage*

Under normal storage conditions, the ethylene evolved during ripening is continuously removed by aeration. In MA storage, however, ethylene is accumulated within the package or the storage environment and influences the product quality. Temperature is an important factor in ethylene production. In general, the rate of ethylene production decreases with decrease in temperature. Even though ethylene is produced at low

temperatures (near 0°C) and remains active, it is not commercially significant (Knee, 1990).

Removing ethylene from the storage atmosphere is desirable for achieving better firmness retention and quality. Usually, the cost of removal is higher than the added benefits. Ethylene can be removed either by chemical oxidation with potassium permanganate or catalytic oxidation (Knee, 1990). In chemical oxidation, the gas atmosphere from the CA or MA room is pumped through beads of activated alumina, which is incorporated with potassium permanganate, and then returned to the CA or MA room. The initial cost is lower, but the maintenance cost is higher than that of catalytic scrubbing (Blanpied, 1990). In catalytic oxidation, the gas in the atmosphere is taken out and heated to 200°C by a heat exchanger and ethylene is scrubbed in the presence of platinum catalyst and the gas mixture is then cooled down to the desired temperature (in the same heat exchanger) and returned to the storage chamber. The initial cost of installation is high and operating cost per tonne of fruit load is the same irrespective of ethylene load (Blanpied, 1990).

4.3. *Hypobaric storage*

Storage at sub-atmospheric pressures has a similar effect of low-O_2 MA storage. Due to product respiration, CO_2 level increases. Due to the vacuum, diffusion of ethylene out of the produce is increased and delays senescence. This method requires a vacuum pump to create vacuum in the storage area, a pressure regulator to regulate the leakage of air into the storage area to maintain a desired low pressure, a humidifier to saturate the storage atmosphere and a refrigerator to control the storage temperature (Burg, 1990). To prevent the moisture loss from the products by evaporation due to low pressure, the storage air is usually maintained at high r.h. of about 90–100%. This type of evaporative cooling is more efficient than convective cooling. Low pressure also reduces the respiratory heat. Hypobaric storage inhibits the growth of fungi, but normal growth rate is resumed on transfer to atmospheric air (Barkai-Golan, 1990).

4.4. *Postharvest disease suppression by modified atmosphere storage*

Vegetables have more available water, less carbohydrates (sugars) and high pH (near to neutral) than fruits (Jay, 1992). Due to more available water and having pH near to neutral, bacteria is the predominant microflora in vegetables. The common spoilage bacteria is *Erwina* spp., which causes bacterial rots in vegetables. The pH of the fruits is below the level to support bacterial growth. Moulds and yeasts (fungi) are major spoilage microorganisms in fruits. Fungi are aerobic organisms and their growth is reduced by storing fruits in low-O_2 atmospheres. The inhibitory effect of CO_2 increases with a decrease in temperature, as in the case of meat.

Modified atmosphere suppresses the postharvest diseases in fruits and vegetables by increasing the host resistance and by affecting the pathogens (Barkai-Golan, 1990). It is a well-known fact that the host resistance to pathogens decreases with ripeness. As fruits ripen, the pectic substances of the middle lamella of the plant cell membrane become more soluble and tissues become softer. The pathogens secrete pectolytic enzymes for which soft tissues are more vulnerable. Modified atmosphere storage reduces the respiration rate and the production of ethylene, thereby delaying the onset of ripening and reducing the rate of ripening. Thus, MA increases the host resistance by delaying fruit softening and maintains the firmness or integrity of fruits which are then less prone to spoilage.

Growth of common postharvest pathogens is greatly inhibited only when the O_2 is reduced below 1%. Usually, all the fruits and vegetables are stored at 2–5% O_2 to prevent oxygen injury and off-odours. At these concentrations, the growth rate of pathogen is merely reduced and therefore the suppression of decay/diseases in fruits and vegetables can be largely attributed to the increase in natural host resistance (Barkai-Golan, 1990). It is important to note that the fruits and vegetables are very sensitive to environmental conditions. If there is a low concentration of O_2 or high concentration of CO_2, or chilling injury, tissue integrity is affected and the tissues are more susceptible to pathogen attack.

4.5. *Storage conditions*

The optimum environmental conditions vary widely even within the same cultivar, but grown at different places. Therefore, the optimal conditions have to be determined for each cultivar in a laboratory, before applying it commercially. Optimal storage conditions for various fruits and vegetables are given in many reviews (Smock, 1979; Isenberg, 1979; Thompson, 1998). Storage conditions for few important fruits and vegetables are presented here.

4.5.1. *Apples*

Modified atmosphere storage is highly successful for extending storage life of apples and is commercially utilized now. Recommended storage O_2, CO_2 and temperature for apples are 2–3%, 1–8%, and −1·0–0·6°C, respectively, and this results in the storage life of

6–7 months (Blanpied, 1990). With such an extension of storage life, growers can sell their produce all year round (Smock, 1979). Modified atmosphere has to be established as soon as possible after the harvesting of apples to achieve maximum retention of flesh firmness. Oxygen concentrations of less than 2% result in low O_2 injury. The first visible evidence of chilling injury is the colour changes from red to blue or purple. Ethyl alcohol accumulates in the plant tissues, resulting in alcohol poisoning due to anaerobic condition, if stored under low O_2 atmosphere for long periods of time.

4.5.2. *Pears*

Pears are usually stored in a MA consisting of 2–3% O_2 and 1–3% CO_2. Elevated levels of CO_2 cause a physiological disorder known as 'brown core' (Smock, 1979). Similar to meats, a small difference in storage temperature near 0°C has a great influence on the storage life of pears. Blanpied (1990) reported that the storage life of Bartlett pears is increased by 40% when the temperature is reduced from 0 to −1°C. Pears lose water and shrivel even at 90% r.h. Therefore, a r.h. of more than 95% has to be maintained (Thompson, 1998). Modified atmosphere storage in conjunction with low temperatures prevents ripening. Pears lose the capacity to ripen or deteriorate after ripening, if stored under MA for long periods of time (200 days) and this is known as overstorage (Blanpied, 1990).

4.5.3. *Tropical fruits*

Chilling injury occurs in many tropical fruits, when they are stored below 10°C. At the same time, the fruits have to be stored just above 10°C to maximize the shelf life. Modified atmosphere is used as a supplement to cold storage preservation. Bananas are usually transported in a MA of 10% O_2 and 10% CO_2 at 13°C. At the destination, controlled ripening of bananas is done by using ethylene (Hatton & Spalding, 1990). Air transport of papayas (*Carica papaya*) is less expensive than the transport of papayas under MA by ship from Hawaii to Japan. Similarly, pineapples are also transported by air commercially rather than using MA transport by ship (Hatton & Spalding, 1990).

Unlike other tropical fruits, citrus fruits have no respiratory system. Therefore, the storage life extension of citrus fruits by MA is not as high as in other tropical fruits. However, quality of citrus fruits can be manipulated by MA storage. Pretreatment of grapefruit by 20–45% CO_2 decreases rind pitting. In lemons, CO_2 delays degreening and intensifies the colour of ripe lemons (Hatton & Spalding, 1990).

4.5.4. *Vegetables*

Relative humidity of 90–95% is recommended for MA storage of most of the vegetables. Modified atmosphere storage of asparagus, broccoli, cabbage and lettuce is promising. For asparagus, the O_2 level must be maintained above 10% to avoid O_2 injury. The recommended CO_2 concentration is 10–14% at 0–3°C and varies greatly with temperature (Leshuk & Saltveit, 1990). Broccoli must be maintained in a MA of 1–3% O_2 and 5–10% CO_2 at 0°C. Recommended O_2 and CO_2 concentrations for storage of cabbage are 2–3 and 3–6%, respectively, at 0°C. Russet spotting, a physiological disorder in lettuce, is inhibited in low O_2 storage. Optimum O_2 concentration for storage of lettuce is 1–3%. Optimum conditions for storage for tomatoes are 5% O_2 and 2–3% CO_2 at 10–20°C. There is no economic advantage in the use of MA storage for horseradish, bell peppers, potatoes, spinach and squash over low-temperature preservation (Leshuk & Saltveit, 1990).

4.6. *Active packaging*

Active packaging finds wide applications in the MAP of fruits and vegetables. The O_2 scavenging system described in Section 3.5 can be used with MAP of fruits and vegetables. Carbon dioxide scavenging or emitting products are commercially available. Active packaging can also be designed to absorb the ethylene actively during storage. Ethylene absorbing sachets (Rengo Co., Osaka, Japan; Alpine, New Jersey, NY) and powders (Derck Rowlands Technology Transfer, Westgate, Kent, UK) are commercially available (Labuza & Breene, 1989). Preservative films are available, which diffuse various preservatives such as nisin, sorbate, glycol, antioxidants, antibiotics, ethanol or ethylene into the package atmosphere slowly to control the microbial growth or to suppress unwanted biochemical reactions (Labuza & Breene, 1989). There are growing interests in developing time–temperature integrators (TTI), which would monitor the product temperature history to determine the remaining storage life. The 3 M Monitor Mark (3 M, St. Paul, MN) is one of the commercially available TTIs, which consists of a dye and a wick. The dye consists of a fatty acid ester. The diffusion of the dye through the porous wick is dependent on the time–temperature history, which is then related to the storage life of the food product. The position of the dye in the wick will show the remaining storage life to consumers. This will greatly improve the inventory control at the retail stores and also food safety. Another commercial TTI is available from I-Point Biotechnology, Reston, VA, which is based on enzymatic hydrolysis of a lipid substrate based on time–temperature history. The

hydrolysis causes a pH change, which results in a colour change (Labuza & Breene, 1989).

5. Conclusions and further research

5.1. *Grains*

For modified atmosphere (MA) storage of grains, an atmosphere containing an elevated level of CO_2 ($>60\%$) with depleted level of O_2 ($<10\%$) at low relative humidities ($<50\%$) and high temperatures ($>27^{\circ}C$) is lethal to most insect species that are responsible for losses in the stored grain. The response may, however, vary depending upon the nature and size of the infestation, the life stages of insect species and other storage conditions. Insects have the potential to develop resistance to modified atmospheres, if modified atmospheres are improperly used. Modified atmospheres do not cause any detrimental effect on functional characteristics of grains and help in maintaining seed germination and viability and prevent mould growth.

Modified atmosphere storage is technologically sound and well proven under laboratory conditions. Success of this technique in farm bins and elevators depends on the development of techniques for sealing existing grain bins. Most of the bins at farms and elevators are not airtight and therefore complete mortality with MA alone is not possible under current conditions. Therefore, MA can be used as one component of an integrated pest management strategy. Now, the applied research is required to take the technology from the laboratory to the field. Developing sealing techniques to improve the gas-tightness of the existing bins is an immediate need and research must be concentrated in this area.

Most of the laboratory studies on grains determined the exposure time for complete mortality of important stored-grain pests at constant elevated concentrations of CO_2 (40–100%). However, it is difficult to maintain a constant level of CO_2 in bins due to leakage. The models for predicting mortality of insects exposed to changing CO_2 concentrations under varying temperatures has to be developed. Even though extensive research has been conducted under laboratory conditions, data on population dynamics of inter- and intra-specific insects under sub-lethal conditions (low CO_2 concentrations of 2–12%, low temperatures of 5–20°C, and high r.h. of 60–90%) are lacking. These data have to be collected to develop a model describing population dynamics of pests over a complete range of environmental conditions. This model can be incorporated into an expert system, that will be useful for day-to-day decision-making by farmers and farm managers. Studies on MA storage of grains as a component of integrated pest management strategy will be useful.

5.2. *Meats*

Effectiveness of modified atmosphere packaging (MAP) is well known to the meat industry and more than 90% of primal and sub-primal meat cuts are transported in MAP (especially vacuum packaging) from the meat packer to the retail outlets. The maximum storage life of fresh meat is achieved, when the meat is stored under 100% CO_2 at $-1{\cdot}5^{\circ}C$. The inhibitory effect of CO_2 increases with a decrease in meat temperature. The selection of lactic acid bacteria reduces the threat from pathogens and assures food safety.

Due to new consumer demands and convenience at retail stores, there is a great interest in developing MAP of consumer-ready cuts. Already some commercial applications of MAP in consumer-ready cuts are found in high-premium markets. This trend will be seen more and more in the coming years. Oxygen scavengers can be used to remove the residual O_2 in the package atmosphere and is a potential research area. The kinetics of absorption of O_2 varies considerably near sub-zero temperatures and have to be studied. When MAP is integrated with active packaging (O_2 scavenging), low-temperature preservation ($-1{\cdot}5^{\circ}C$), and high processing hygiene, MAP consumer-ready products will be economically viable not only for high-premium meat cuts but also for other low-priced meat cuts. Research is required on integrating MAP and active packaging to make it a commercially successful technology. Temperature abuse is common and is one of the major sources of food-borne illness outbreaks. Therefore, research is needed on testing and calibrating various commercially available TTI on MA packages for different meat products. This will greatly improve the food safety.

5.3. *Fruits and vegetables*

Modified atmosphere packaging is used as a supplement to low-temperature preservation of fruits and vegetables. It is mainly used to reduce respiration rate and retard ripening process, thereby increasing the host resistance to diseases. Commercially, MA is successful for storage of apples and pears. Marginal increases in storage life and quality by MA storage is not enough for the added cost of implementing MA technology commercially for most vegetables. An important problem in the commercial application of MA in fruits and vegetables is that the effect of MA is different for the

same cultivar grown in different locations or under different cultural practices or different seasons. Therefore, trial-and-error studies have to be conducted to determine the optimum atmosphere for each cultivar in a given place and season.

Today, packaging of films of any desired values of transmission rates of O_2, CO_2 and water vapour are available. Models describing the respiration rate of a fruit or vegetable and gas exchange between the MA in the package and ambient atmosphere should be developed. Based on the model, it is possible to maintain a self-controlled atmosphere, *i.e.* constant gas mixture throughout the storage period, by selecting appropriate initial gas mixture, properties of the packaging film and right storage temperature. As fruits and vegetables are more sensitive to environmental conditions, the conditions have to be controlled precisely to achieve superior product quality and the development of models for different fruits and vegetables is a pre-requisite. Research is also needed in integrating active packaging with MAP to make this technology economically viable. Current ethylene removing techniques (catalytic or chemical oxidation) are not commercially successful. Active packaging involving ethylene-absorbing substances should be studied.

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