Diffusion Channel System for Enhancing the Shelf Life of Fruits and Vegetables under Controlled/ Modified Atmosphere

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Abstract

Fruits and vegetables generally have a short shelf life and begin to lose their freshness shortly after being plucked from the tree. This is because of the metabolic activities, which continue even after harvest. Respiration is one of the major metabolic activities, which involve the consumption of oxygen (O_2) and evolution of carbon dioxide (CO_2) along with water and energy in the form of heat. Controlling the respiration rate and other metabolic activities, minimize the physiological disorders such as rapid ripening, senescence, growth of mould, decay, degradation of chlorophyll and loss of vitamins. The respiration rate can be restricted by controlling temperature, relative humidity and altering the natural gas composition such as O_2 and CO_2. The modification process often tries to reduce the level of O_2 and increase the level of CO_2 initially and it changes dynamically depending on the produce and permeability of the packaging materials. Whereas in controlled atmosphere (CA) condition their levels are altered within air tight storage and maintain their optimum levels throughout the storage period suitable to the commodities. The desired gas composition in CA storage may be achieved either by static method where the product generates the atmosphere or by flushing method where a flowing gas stream purges the storage continuously, providing the storage atmosphere. In this paper, general aspects of the respiration process, important beneficial effects, detrimental effects, principles of gas diffusion, diffusion channel system and highlights of research related to CA storage with diffusion channel are presented.

1. Introduction

Perishable foodstuffs such as fruits and vegetables deteriorate in the presence of air due to the chemical effect of atmospheric oxygen as well as microbiological degradation. Many forms of food preservation such as drying, cold storage, vacuum packaging, modified atmospheric packaging, etc. have been studied and commercially implemented during the past years. The main advantage of drying using these methods is the low water activity in dried materials, which retards microbiological spoilage. On the other hand, drying process causes many physical and chemical changes (shrinkage, cracking, loss of vitamins, etc.), which are usually irreversible and undesirable. Storage is a method of preservation of fruits and vegetables after harvest either temporary or for long term depending upon the commodity, demand, market value, etc. Proper storage prolongs the shelf life of fruits and vegetables and prevents gluts in the market. Among the storage techniques, controlled atmosphere (CA) and modified atmosphere (MA) storage is the best option to store for a longer period without changing the food value. Though the research on CA started in 1819 by Berard and followed by Nyce in 1860, the CA systems became the most important innovation since the introduction of mechanical refrigeration (Kays, 1991). Kidd and West first reported the beneficial effect of CA storage in maintaining the quality of certain varieties of apples in 1927. Since then efforts have been made to apply the CA technology to various fruits and vegetables in general (Smock, 1979; Raghavan et al., 1984 and Wills et al., 1989).

2. Plant Metabolism

Fruits and vegetables are living organisms, which undergo biological processes associated with life. To sustain the biological activities, they draw energy through respiration from the starch, sugars and other products of photosynthesis. The substances used for respiration are continually replaced through photosynthesis when they are still attached to the plant. Once they are harvested, photosynthesis ceases and there is no replacement for the substances. The biological process that keeps the cell alive slows down and the cell structure breaks down. As a consequence they have a short shelf life and begin to lose their freshness shortly after being plucked from the tree (Phan et al., 1975; Wills et al., 1989 and Kays, 1991).

The major physiological activity in the post harvest life of a fruits and vegetables is respiration. It is a metabolic process involving the consumption of oxygen (O_2) for oxidative breakdown of organic components present in cells such as starch, sugar, acids, fats, proteins into simple molecules such as carbon dioxide (CO_2), water along with the concurrent production of energy and other intermediates which can be used by the cell for synthetic reactions. Respiration occurs in the presence of oxygen is termed aerobic respiration. The normal substrate for respiration is glucose, and the chemical reaction is given as follows (Burton, 1982 and Wills et al., 1989)

The rate of respiration is an index of the metabolic turnover in the produce and is believed to be proportional to the rate of deterioration. The higher the rate, the faster the deterioration

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{Energy} \quad \text{------------------------(1)}$$

rate because of the increase in the breakdown of the organic compounds stored in the harvested product. Respiration is considered to be key process which brings some physiological disorders such as ripening, senescence, browning, molding, degradation of chlorophyll, decay and subsequently deterioration in their normal course of time (Phan et al., 1975; Kays, 1991 and Kader, 1992).

Anaerobic respiration occurs when the availability of oxygen is insufficient. This result in the conversion of glucose into lactic acid or acetaldehyde and ethanol, a process termed as fermentation. The O_2 concentration at which anaerobic respiration commences is known as the extinction point and varies between tissues. Anaerobic respiration gives off an alcoholic odor and an off-flavour (Gariepy et al., 1988 and Wills et al., 1989). The respiration rate of produce can be restricted by proper controlling temperature, relative humidity and natural atmospheric condition. The CA or MA storage of fresh produce relies on modification and controlling of the atmosphere inside the storage, achieved by the natural interplay between two processes, the respiration of the product and the transfer of gases through the packaging, that leads to an atmosphere richer in CO_2 and poorer in O_2. This atmosphere can potentially reduce respiration rate, ethylene sensitivity and production, decay and physiological changes (Kader, 1987 and Kader et al., 1989).

3. Modified Atmosphere

Modified atmosphere (MA) is the practice of modifying the composition of the internal atmosphere of a package in order to improve the shelf life. The modification process often tries to reduce the level of O_2 and increase the level of CO_2 initially and it changes dynamically depending on the produce and permeability of the packaging materials in order to slow down the growth of aerobic organisms and the speed of oxidation reactions (Jayas and Jeyamkondan, 2002). The oxygen can be replaced with nitrogen (N_2), or carbon dioxide (CO_2), which can inhibit the growth of microorganisms (Parry, 1993). Modified atmosphere packaging (MAP) is a preservation technique in which the composition of normal atmospheric air surrounding the food material in the package is changed to another composition. By reducing the O_2 level and increasing the CO_2 level, ripening of fruits and vegetables can be delayed, respiration and ethylene production rates can be reduced, softening can be retarded and various compositional changes associated with ripening can be slowed down (Phillips, 1996 and Day, 1996).

4. Controlled Atmosphere

Precise control of the respiratory gases in modified atmosphere leads to controlled atmosphere. It requires precise control of O_2 and CO_2 concentration around fresh produce and it is more appropriate for long-term storage. Controlled atmosphere storage (CAS) is a system for creating an appropriate atmospheric condition that differs substantially from normal air composition (about 78% N_2, 21% O_2, and 0.03% CO_2) in respect to CO_2 and O_2 levels. The CAS is also defined as the alteration or adjustment of the O_2 and CO_2 levels within gas tight stores or containers and constant monitoring of their optimum levels throughout the storage period suitable to the commodities. Generally, O_2 below 8% and CO_2 above 1% are used (Raghavan and Gariepy, 1985 and Kader, 1986).

Atmospheric modification should be considered as a supplement to maintenance of optimum ranges of temperature and RH for each commodity in preserving quality and safety of fresh fruits, vegetables, and their products throughout post harvest handling. The gas mixture will constantly change due to metabolic activity of the respiring fruits and vegetables in the store. The gases are therefore measured periodically and adjusted to the predetermined level by the introduction of fresh air or nitrogen or passing the store atmosphere through a chemical to remove carbon dioxide (Thompson, 1998). In order to achieve and maintain a satisfactory atmosphere within storage, gas permeability of selected films must be such that they allow oxygen to enter the storage at the rate offset by the consumption of oxygen by the commodity. Similarly carbon dioxide must be vented from the storage to offset the production of carbon dioxide by the commodity.

The actual effects that varying levels of O_2 and CO_2 in the atmosphere have on crops varies with such factors as: (i) the species and cultivars of crop (ii) the state of maturity of the crop at harvest and crop temperature (iii) growing conditions before harvest (iv) the degree of ripeness of the climacteric fruit (v) concentration of the gases in the store (vi) presence of ethylene in the store (Zagory and Kader, 1988).

5. Advantages of CA/MA Storage

The controlled atmosphere storage has many advantages and is summarized as follows (Gariepy et al., 1984; Dilley, 1983 and Wills et al., 1989).

(i) An extension in storage life which can even be doubled by considerable decrease in respiration rate as much as the over ripening is delayed. Some physiological alterations such as growth of mold, rotting, decay, pink rib, butt discolouration, browning, chill injuries and russet spotting is minimized greatly in CA storage condition.

(ii) The CA system can maintain the quality of produce for longer periods by its influence on metabolic processes, minimizing loss of some organic acids and vitamins. It prevents the subsequent deterioration of the produce against the imposition of stress injury, death of pathogenic organisms and retard senescence.

(iii) A reduction in the effect of ethylene on metabolism due to the interaction of O_2 with ethylene, with a consequent delay of appearance of senescence symptoms.

(iv) Limited degradation of chlorophyll, with a consequent higher stability of original colour is retained in CA storage. The CA has proven to be effective in minimizing moisture loss and chilling injury thus maintaining a firm and succulent texture of the commodities.

(v) The minimally processed mixed vegetable, whose shelf life is deemed to be too short, can also be stored for longer periods.

(vi) The CA systems have favored in extending marketing season, high economic returns and wide distribution of the produce.

6. Different Techniques for MA/CA Storage Conditions

CA/MA storage should be carefully designed, as a system incorrectly designed may be ineffective. The design of CA storage depends on a number of variables such as characteristics of the product, mass, temperature, atmospheric gas composition, permeability of the packaging materials to gases, respiration rate of the product as affected by different gas composition, water vapour transmission rate and sealing reliability (Smock, 1979; Zagory and Kader, 1988 and Phillips, 1996). MA storage technique involves either actively or passively modifying the atmosphere surrounding the product within a package. Active modification occurs by the displacement of gases in the package, which are then replaced by a desired mixture of gases, while passive modification occurs when the product is packaged using a selected film type, and a desired atmosphere develops naturally as a consequence of the product's respiration and the diffusion of gases through the film (Day, 1996; Zagory and Kader, 1988).

CA storage involves atmospheric gas mixtures and their diffusion characteristics. Gas diffusion describes the spread of particles through random motion from regions of higher concentration to regions of lower concentration. There are different techniques to provide the desired gas composition in the storage environment depending mainly on the degree of control of the gases. Some researchers prefer to use the terms static controlled atmosphere storage and flushed controlled atmosphere storage. 'Static' is where the product generates the atmosphere and 'flushed' is where the atmosphere is supplied from a flowing gas stream, which purges the store continuously. Systems may be designed which utilize flushing initially to reduce the O_2 content then either injecting CO_2 or allowing it to build up through respiration, and then maintenance of this atmosphere by ventilation and scrubbing (Dilley, 1983; Raghavan and Gariepy, 1985; Phillips, 1996 and Ratti et al., 1998). From a design point of view, they can be classified into (i) oxygen control system (ii) carbon dioxide control system (iii) hypobaric system (iv) membrane systems and (v) diffusion channel system (Dilley, 1983; Raghavan et al., 1982 and Ratti et al., 1998).

7. Suggested CA Conditions for Fruits and Vegetables

The storability of fruits and vegetables is strictly related to their respiration rate, which is an expression of metabolic activity. Aerobic respiration requires O_2 and results in CO_2 and heat release. More than 95% of the energy released is lost as heat. The temperature decreases particularly in modification of the atmosphere. This leads to a reduction in respiration rate, and therefore, to an increase in storage life in fruits with climacteric respiration. Selection of the most suitable atmosphere depends on cultivars, stage of maturity, environmental and cultivation parameters. No one atmosphere is best for all produce, specific recommendations and cautions must be determined for each crop over the range of storage temperature and periods. Suggested CA/MA conditions for some of deciduous fruits, tropical and subtropical fruits and vegetable species are presented in Table 1, 2 and 3 respectively.

8. Detrimental Effects of MA/CA Storage

There are some evil effects in controlled atmosphere storage when the gas composition is above or below the optimum levels (Kader et al., 1989 and Day, 1996).

Table 1: Suggested atmospheric condition for storage of deciduous fruits under CA/MA storage

Commodities	CA condition				Storage life	References
	T (°C)	RH (%)	O_2 (%)	CO_2 (%)		
Apricot	0-5	90-95	1-3	1-5	1-3 weeks	Thompson (1998)
Blackberries	0-5	90-95	5-10	15-20	3-6 days	Talasila et al. (1992)
Blueberry	4.5	90-95	6-21	0-15	10-18 days	Song et al. (1992)
Cherries, sour	0-5	90-95	3-10	10-12	3-7 days	Shewfelt (1986)
Cherries, sweet	0-5	90-95	3-10	10-15	2-3 weeks	Shewfelt (1986)
Fig	0-5	85-90	5-10	15-20	7-10 days	Hardenburg et al., 1986
Grapefruit	0-5	85-90	3-10	5-10	6-8 weeks	Kader et al. (1989)
Kiwifruit	0-5	90-95	1-2	3-5	3-5 months	Hardenburg et al., 1986
Peach	0-5	90-95	1-2	3-5	2-4 weeks	Kader et al. (1989)
Pear Asian	0-5	85-90	2-4	2.5	2-6 weeks	Thompson (1998)
Pear European	0-2	90-95	1-3	0-5	2-7 months	Thompson (1998)
Plums	0-3	90-95	1-2	0-5	2-5 weeks	Kader et al. (1989)
Raspberry	0-5	90-95	5-10	15-20	3-6 days	Joles et al. (1994)
Strawberries	0-5	90-95	5-10	15-20	7-10 days	Renault et al. (1994)

Table 2: Suggested atmospheric condition for storage of tropical and subtropical fruits under CA/MA storage

Commodities	CA condition				Storage life	References
	T (°C)	RH (%)	O_2 (%)	CO_2 (%)		
Avocado	3-13	85-90	2-5	3-10	1-4 weeks	Young et al. (1962)
Apple	-1-4	90-95	2-3	1-2	1-7 months	Lalakul et al. (1999)
Banana	10-15	85-90	2-5	2-5	1-4 weeks	Maneerat et al. (1997)
Custard apple	13	90-95	3-5	5-10	2-4 weeks	Kader et al. (1989)
Grapes	0-5	90-95	2-5	1-3	1-4 weeks	Kader et al. (1989)
Lemons	9-15	85-90	5-10	0-10	1-6 months	Young et al. (1962)
Lime	5-10	85-90	5-10	0-10	6-8 weeks	Thompson (1998)
Litchi	1-2	90-95	3-5	3-5	3-5 weeks	Zagory & Kader (1988)
Mango	10-15	85-90	3-5	5-10	2-3 weeks	Fishman et al. (1996)
Olive	5-10	85-90	2-3	0-1	4-6 weeks	Thompson (1998)
Orange	3-10	85-90	2-10	0-10	3-12 weeks	Thompson (1998)
Papaya	7-15	85-90	2-5	5-8	1-3 weeks	Thompson (1998)
Pine apple	7-15	85-90	2-5	5-10	2-4 weeks	Thompson (1998)
Pomegranate	5-10	90-95	3-5	5-10	2-3 months	Thompson (1998)

(i) Generally, when the fruits and vegetables kept under controlled or modified atmosphere condition, consume oxygen and liberates carbon dioxide and water. The absence of O_2 can lead to anaerobic respiration which accelerates senescence and spoilage due to fermentation.

(ii) Irregular ripening of fruits, such as banana, mango, pear, and tomato, can result from exposure to O_2 levels below 2% and/or CO_2 levels above 5% for more than 1 month.

(iii) Certain physiological disorders such as internal browning in apples and pears, brown stain of lettuce may possibly be aggravated. Susceptibility of decay is increased when the fruit is physiologically injured by too low O_2 or too high CO_2 concentrations.

(iv) Off-flavors may be developed at very low O_2 levels (as a result of anaerobic respiration) and very high CO_2 levels (as a result of fermentative metabolism).

(iv) Reduction of sensitivity to ethylene action at O_2 levels less than 8% and/or CO_2 levels more than 1%. Low O_2 (<1%)

Table 3: Suggested atmospheric condition for storage of vegetables under CA/MA storage

Commodities	CA condition				Approx. storage life	References
	T (°C)	RH (%)	O_2 (%)	CO_2 (%)		
Beans, snap	5-10	95	2-3	4-7	7-10 days	Thompson (1998)
Broccoli	0-5	95-100	1-2	5-10	10-14 days	Talasila et al. (1994)
Brussels sprouts	0-5	95-100	1-2	5-7	3-5 weeks	Isenberg (1979)
Cabbage, Chinese	0-5	95-100	1-2	0-5	2-3 months	Gariepy et al. (1984)
Cabbage, late crop	0-5	95-100	3-5	3-7	5-6 months	Gariepy et al. (1984)
Cauliflower	0-5	95-98	2-5	2-5	3-4 weeks	Ratti et al. (1996)
Corn, sweet & baby	0-5	95-98	2-4	5-10	5-8 days	Thompson (1998)
Cucumbers, slicing	8-12	85-90	3-5	0-5	10-14 days	Pal & Boucher (1995)
Cucumbers	4	95-100	3-5	3-5	7 days	Pal & Boucher (1995)
Garlic bulb	-1-5	65-70	0.5	5-10	6-7 months	Thompson (1998)
Leeks	0-5	95-100	1-2	3-5	2 months	Gariepy et al. (1984)
Lettuce	0-5	98-100	2-5	0	2-3 weeks	Smyth et al. (1998)
Mint	0-5	95-100	5-10	5-10	2-3 weeks	Thompson (1998)
Mushrooms	8	90	1-21	1-10	7-14 days	Thompson (1998)
Okra	8-12	90-95	Air	4-10	7-10 days	Thompson (1998)
Onions, dry	0-5	65-70	1-3	5-10	1-8 months	Pal & Boucher (1995)
Onions, green	0-5	95-100	2-4	8-20	3 weeks	Thompson (1998)
Peas in pods & snap	0-5	90-98	2-3	2-3	1-2 weeks	Isenberg (1979)
Radish	0-5	95-100	1-2	2-3	1-2 months	Isenberg (1979)
Spinach	0-5	95-100	5-10	5-10	10-14 days	Burgheimer et al.1967
Tomatoes, green	9-20	90-95	3-5	2-3	2-5 weeks	Yang & Chinnan(1988)
Tomatoes, ripe	8-12	85-90	3-5	0-5	1-3 weeks	Yang & Chinnan (1988)

and/or elevated CO_2 (40 to 60%) can be a useful tool for insect control in some fresh and dried fruits, flowers, vegetables, dried nuts and grains.

9. Diffusion Channel System

Most of the work on CA/MA has been on polymeric film packaging. These films are limited to their permeability where high CO_2 is desired (Zagory and Kader, 1988). Their performance can be improved by use of perforations. Such perforations are related to diffusion channels with a length of equal to the thickness of the film (Beugerod, 1980 and Rarnachandra et al., 1995). Some technological and economical limitations associated with the membrane and other systems could be solved by use of diffusion channels (Baugerod, 1980; Ratti et al., 1998 and Ramachandra et al., 1995). In the diffusion channel system, maintaining the steady state concentration of gases between inside and outside storage chamber result prevents the alcoholic fermentation due to anaerobic respiration.

10. Principles of Gas Diffusion

Controlled atmosphere storage involves atmospheric gas mixtures and their diffusion characteristics. Gas diffusion describes the spread of particles through random motion from regions of higher concentration to regions of lower concentration. Diffusion occurs in response to a concentration gradient and is expressed as change in concentration due to a change in position (Figure 1). The gas diffusion generally obeys Fick's first law of diffusion, which states that the gas flux moves from region of higher concentration to region of lower concentration, with a magnitude that is proportional to the concentration gradient. The movement of the gases is due to the random motion of the individual molecules caused by their kinetic energy.

The gas flux can be mathematically expressed as follows:

Where,

$$J = - D \frac{\partial C}{\partial X} \quad \text{........} (2)$$

J = rate of gas diffusion (amount of gas that will flow from one point to another point through a unit area unit^{-1} time), (mol m^{-2}.s) ; D= diffusion coefficient or diffusivity that describes the speed of gas diffuses, m^2 s^{-1}; C= concentration of ideal gas mixture, mole m^{-3}; ∂C= change in concentration of gas; x= length of gas diffusion path, m; ∂x= distance between where the object started and where it ended up after it diffused; '-' sign indicates that J is positive when movement is down the gradient

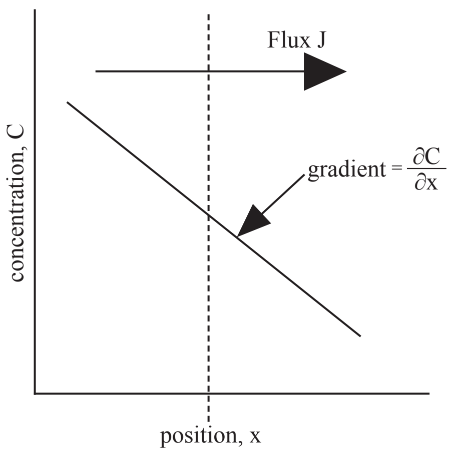

Figure 1: Principles of gas flux

In steady state conditions, the diffusion rate of a gas is proportional to the concentration difference across the material and the area perpendicular to the diffusion. It is however, inversely proportional to the length of the gas diffusion path between the two concentration levels.

11. Principles of Diffusion Channel System

Bird developed controlled atmosphere storage using diffusion channel in 1960 and it is working basis on the principle of Fick's first law of gas diffusion cited by Kader (1992). Baugerod (1980) described the principle behind the diffusion channel in controlling gas levels in the CA storage. Diffusion channel is a fiberglass hollow tube fitted with airtight storage chamber in which commodities are stored and the other end of the tube is exposed to the ambient air. Diffusion of gases takes place through the channel due to the concentration gradient of gases created between inside the storage chamber and the outside atmospheric air and thereby a modified atmosphere is created inside the chambers, which is constructive for the storage. Figure 2 shows the schematic diagram of the diffusion channel system.

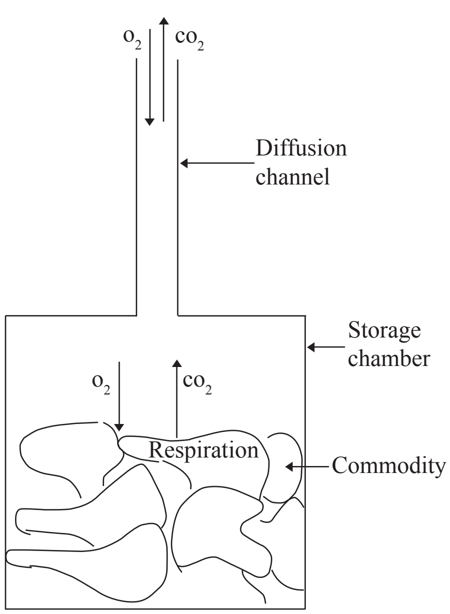

Figure 2: Schematic diagram of diffusion of gasses through diffusion channel during storage

During the respiration of the commodity, O_2 is consumed and CO_2 is liberated, resulting in a change of concentration of O_2 and CO_2 inside the chamber. With respect to ambient condition, the concentration of O_2 decreases and that of CO_2 increases at rates depending on the respiration rate (RR) and respiration quotient (RQ) of the produce. This creates concentration gradients between outside and inside of storage chamber. Due to concentration gradient, O_2 diffuses from the chamber outside to inside and CO_2 diffuses from the chamber to outside through the channel. The maintenance of required levels of steady-state concentration of the gases inside the chamber depends upon the mass of the commodity stored, RR, RQ and rate of diffusion of the gases. The rate of diffusion also depends on the length and cross-sectional area of the channel/tube.

Varying the dimensions of the diffusion channels could easily alter the gas composition in the storage chambers. It is also possible to attain gas levels higher than in the membrane system. In this system, the quality of stored produce is also well maintained as compared to other systems. Diffusion channel is used due to its extreme structural simplicity, which provides great flexibility in the design of storage chamber and the materials used are considerably less expensive.

12. Factors Affecting the Steady State Concentration

The maintenance of required steady state concentration levels of gases inside the chamber was dependent upon the mass of the commodity stored, respiration rate, respiration quotient and the rate of diffusion of the gases. The rate of diffusion was also dependent on the length and cross sectional area of the diffusion channel and the difference in concentration of O_2 and CO_2 between the chamber and the ambient air as created by metabolic activity of the produce. The respiration rate of stored products can be determined by the concentrations of CO_2 or O_2 with time when the commodity is placed in a closed chamber using the following equation (Lee et al. 1991).

Where,

$$r = \frac{dCO_2 \times V}{dt \times M_S} = \frac{dCco_2 \times V}{dt \times M_S} \quad \text{-------} (3)$$

r= rate of respiration, mg kg^{-1} h^{-1}; CO_2= concentration of O_2 inside the storage chamber, mg l^{-1}; Cco_2= concentration of CO_2 in storage chamber, mg l^{-1}; V= free volume of the chamber, l^{-1}; M_s= mass of the stored product, kg; dt = change in time, hr.

The respiration quotient (RQ) can be calculated using the equation (Gariepy et al., 1984):

Where,

$$RQ = \frac{RRco_2(vol)}{RRo_2(vol)} \quad \text{------------} (4)$$

$Vo_2(t)$ = volume of O_2 at time t; $Vo_2(t + \Delta t)$= volume of O_2 at time $(t + \Delta t)$; $Vco_2(t)$= volume of CO_2 at time t; $Vco_2(t + \Delta t)$ = volume of CO_2 at time $(t + \Delta t)$

13. Highlights of Research on CA/MA Storage with Diffusion Channel

Baugerod (1980) proved that in storage chamber which were sufficiently airtight, the necessary exchange of CO_2 and O_2 could be achieved by fiber glass channels of varying cross-sectional area which connected to the storage chamber with a vessel containing a CO_2 absorbing material. He stated that a gas composition could be maintained with 1-2% O_2 and 10% CO_2 for several weeks without adjustments and was insensitive to changes in barometric pressure and cyclic fluctuations of the temperature in the storage room.

Celis and Stenning (1995) designed and constructed low cost storage system based on the principle of steady state diffusion. The system was developed by$1.0\times0.75\times0.6$ m^3 PVC container. It was provided with two diffusion channels, one for oxygen equilibrium and other for carbon dioxide. The RH was controlled by means of saturated solution contained in the channel especially designed for the purpose as well as to provide good airtight operation. A dynamic equilibrium is established between the rate of respiration and the rate of diffusion of gases in and out of the system.

Ramachandra et al. (1995) conducted an experiment on storage of broccoli with diffusion channels of cross sectional area 0.04, 0.18 and 1.15 cm^2 and lengths of 0.6, 3, 7, 12, 18 and 25 cm. They concluded that the length and cross sectional area of the channel had a significant effect on the final O_2 concentration level. Increasing the length of channel decreased the oxygen level. The channel lengths of 12 cm and above were able to maintain O_2 concentration level of 2% whereas the channel lengths of 7 cm and blow maintained between 19 and 21%. The cross-sectional area had no significant effect when the length of the channel was 18 cm and more. They also concluded that diffusion channels were effective tools in maintaining the desired O_2 concentration level inside the storage chamber of broccoli. A model based on the molecular diffusion theory has been developed to predict the length of diffusion channel to maintain the desired level of O_2 concentration for a given cross sectional area and mass of broccoli stored.

Ratti et al. (1996) found that the diffusion channels used in the cauliflower MA storage experiments were able to maintain the desired concentration of O_2 during the storage with enough flexibility to account for the fluctuations in storage temperature. The analysis of the effect of the length of diffusion channels upon the final concentration of O_2 in the chamber showed that there were no appreciable differences in O_2 concentrations when the lengths exceeded 0.25 m. After 33 days of storage, the best product quality was observed in the chambers equipped with a 0.25 m diffusion channel length. The O_2 level maintained in these chambers was about 2.5%.

Chimphango et al. (1997) stated that diffusion channels were capable of maintaining the desired gas concentration for CA storage of spinach. The O_2 levels decreased as the length of the diffusion channel increased, conversely CO_2 levels increased with an increase in the length. However, both O_2 levels were quite distinct as the cross sectional area of the channels increased.

Ratti et al. (1998) studied storage of cauliflower under modified atmosphere using diffusion channels. The composition of O_2 in the modified atmosphere storage chambers of cauliflower was regulated through the diffusion of O_2 in narrow channels. Fresh cauliflower was stored at 2.5°C in laboratory chambers equipped with channels of internal diameter 2 mm and of different lengths. This technique was shown to be capable of maintaining different steady state modified atmosphere composition (O_2 from 1.5 to 18%, depending on the length of the diffusion channels and the mass of the product; CO_2 = 0%, with the help of a chemical adsorbent) for long periods of time.

Filipa et al. (1999) conducted studies with a glass jar fitted with a small brass tube inserted in the lid of the jar. It was adopted as the container that would provide the modified atmosphere for strawberries. A brass tube having 40 cm long and 12 mm inside diameter was used with the CO_2 and O_2 transmission rates were 2.54×10^{-6} mol/s/atm and 2.98×10^{-6}-mol s^{-1} atm^{-1} respectively at 19°C could achieve better results for strawberries.

Silva et al. (1999) studied the effect of tube, which can serve as mediator of gas exchange between the package and surrounding atmosphere. Gas permeability through the tube of different sizes was measured at different temperature of 1.5, 7 and 15^{o} C. It was found that the length and diameter of the tube and the temperatures of the surrounding atmosphere significantly affected gas permeability through the tube. The oxygen permeability was more compared to carbon dioxide in the tubes of same dimensions.

Rennie et al. (2003) conducted a study to determine the gas behavior and composition in modified atmospheric storage chambers equipped with diffusion channels. Zucchinis were stored at 7°C for 20 days in laboratory-scale storage chambers equipped with diffusion channels with different lengths. Three different lengths were used, all with the same inside diameter of 1 mm. Calcium hydroxide ($Ca(OH)_2$) was used in some chambers to obtain low CO_2 levels. No conclusive differences were found between the gas concentrations achieved with different lengths of the diffusion channels. Chambers with $Ca(OH)_2$ had 2.2 % O_2 versus 1.8 % O_2 for chambers without $Ca(OH)_2$. It is proposed that the absorption of CO_2 by the $Ca(OH)_2$ reduced the pressure in the chamber resulting in a net flow of ambient air into the chamber. Mass loss of the zucchinis was 2.5 % in chambers with $Ca(OH)_2$ and 1.1 % without $Ca(OH)_2$. This work shows that diffusion channels can have significant flow through the channels due to pressure differences and this should be accounted for in future models of diffusion channel storage.

Stewart et al. (2005) studied on potential of diffusion channel systems to preserve the quality and extend the shelf life of Cavendish bananas. Bananas were stored for 42 days at 15°C under MA conditions using diffusion channel systems. The respiration rate under MA at 15°C was estimated as 20% or 60% less, or 20% greater than that measured in regular atmosphere at the same temperature. Three different diffusion channel lengths (4, 7 and 10 cm) were tested. Results showed that the estimation of a 60% reduction in respiration rate was most accurate. The gas levels in shortest diffusion channel were achieved 5% CO_2 and 3% O_2 in 12-16 days. Fruits in these atmosphere remained unripe for 42 days, had harvest-fresh appearance, good colour and minimum mould compared with controls and fruit stored in different gas compositions.

14. Conclusion

Controlled atmosphere storage for preservation of fruits and vegetables is efficient to retain better quality, longer storage period, longer shelf life and more environmental friendly storage. CA is primarily employed to reduce respiration rate and retard ripening process. CA storage is also used as a supplement to low-temperature preservation. Commercially, CA is successful for storage of many fruits and vegetables such as apples and pears. Marginal increases in storage life and quality by CA storage is not enough for the added cost of implementing CA technology commercially for most vegetables. An important problem in the commercial application of CA in fruits and vegetables is that the effect of CA 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. Research is also needed in integrating active packaging with CAS to make this technology economically viable.

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