KOREAN J. POST-HARVEST SCI. TECHNOL. AGRI. PRODUCTS
Vol. 1, No. 2, pp. 125~131(1994)

Review

Designing Modified Atmosphere Packaging for Fresh Produce

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Introduction

After harvest, fresh produce continues to respire, taking in oxygen and giving out carbon dioxide. The process of respiration in fresh produce may be represented by the following chemical reaction which involves the oxidation of organic substrates (such as starch, sugars, and organic acids) to CO_2 and H_2O along with energy generation.

$$C_6H_{12}O_6+6O_2\rightarrow 6CO_2+6H_2O+\text{energy} \qquad (1)$$

Aerobic respiration involves a series of enzymatic reactions that takes place through the metabolic pathways of glycolysis, the tricarboxylic acid(TCA) cycle, and the associated electron transport system (Kader, 1987). The respiration rate is often a good index of the storage life of the produce: the lower the respiration rate, the longer the storage life.

Modified atmosphere packaging(MAP) is based on the principle of reducing the rates of respiration and ethylene production, retarding physiological, pathological and physical deteriorative processes occurring in a produce, by creating and maintaining an optimum atmosphere(usually reduced O_2 and elevated CO_2 levles) inside a permeable package containing the produce. The optimum package atmosphere can be created by either the acitive modification method or the passive modification method. In the acitive modification method, the optimum package atmosphere is created rapidly by flushing the headspace of the package with a desired gas mixture. In the passive modification method, the optimum package atmosphere is created, at a slow rate, by allowing the produce to respire inside the package to attain equilibrium. In both cases, the optimum atmosphere is maintained by using a properly selected permeable package to control the influx of O_2 and the effulx of CO_2.

Trial-and error approaches are often used to select MAP for fresh produce. An example of such approach involves simply placing a produce inside several packages, monitoring the storage quality of the produce, and comparing the effectiveness of the packages. However this approach is often ineffective and leads to poor results. This paper outlines a systematic approach that uses a simple mathematical model to relate the respiration rates, the package paramentrs, and the environmental facotrs for desinging MAP. The needs for future research on developing MAP for fresh produce are also discussed.

Optimum Gas Composition

Figure 1 presents a flow chart of the design process. The first task is to determine whether controlled atmosphere storage could indeed extend the keeping quality fo the fresh produce in question. If so, it is also necessary to establish the optimum gas composition, and the CO_2 and the O_2 tolerance limits of the produce. These tolerance limits are two of the constraints for MAP design. CO_2 concentrations higher than the tolerance limit induce unfavorable physiological disorder such as breakdown of internal tissues. O_2 concentrations lower than the tolerance limit induce anaerobic respiration, formation of alcohols and aldehydes, and off-flavor and odor development.

A literature review is a good start to gather preliminary information on the optimum gas composition, and CO_2 and O_2 tolerance limits, and the applicability of controlled atmosphere storage and modified atmosphere packaging to the produce. Optimum gas compositions are often presented conveniently as windows, as shown in Figures 2 and 3. The wider the window, the easier it is to maintain the produce within the acceptable limits. A drawback of the literature database is that many critical details, such as the criteria used for determining the optimum gas composition, are seldom reported. Thus it is often necessary for the investigator to conduct his or her own experiments.

To determine the optimum gas composition experimentally, a set of objective and/or subjective quality attributes whcih are measurable, reproducible, and relevant to the produce must be identified. Examples of such quality attributes for fresh produce are color intensity, taste, flesh firmness, strach and soluble sugar content, pH and tiratable acids, weight loss, etc. The experimental design usually includes two or more different temperatures, and for each temperature, the effects of various levels of O_2 and CO_2 (between 0 to 21%) on the selected set of quality attributes as a function of storage time are studied.

The above experiments can be conducted using the open system method (lee, 1987). Produce samples are palced inside airtight jars at constant temperature. Each jar has an inlet port and an outlet port, through which a sufficiently high flow rate of a gas of known concentration is passed over the produce. The quality attributes are monitored as a function of storage time by periodically taking samples from the jars for evaluation.

The study usually involves conducting experiments with several jars simultaneoulsy, each jar representing a predetermined gas composition and temperature combination.

The experimental result if used to compare the effectivehess of controlled atmosphere storeage to that of air storage. If controlled atmosphere storage is found to be more effective, further work is justified to determine the feasibility of developing MAP for the produce. In this case, a window of optimum gas composition, as well the O_2 and the CO_2 tolerance limits should also be determined. If controlled atmosphere storage is found to have the same or lower effectiveness, no further work is warranted.

Respiration Rates

Respiration is affected by internal factors and external factors. Internal facotrs include the type of produce, cultivar, maturity, climacteric or nonclimacteric frutis, gas-diffusion through the plant tissue and the skin, etc. External factors includes temperature, ethylene concentration, CO_2 and O_2 concentration, and stress. Temperature is the most important external facotr because of its dramatic effect on respiration and other biological reactions. The respiratory quotient(R. Q.), the ratio of CO_2 produced to O_2 consumed, ranges from 0.7 to 1.3 depending upon the metabolic substrate(Kader, 1987; Kader et al., 1989), and is affected by the Co_2 and O_2 concentration. The respiration rate is also governed by diffusion of CO_2 and O_2 throygh the plant tissues and the skin.

To design MAP for fresh produce, it is necessary to obtain respiration as a function of O_2 concentration, CO_2 concentration, and temperature. Respiration can be measured with the technique described by Haggar et al.(1992). This technique involves first measuring the respiration rates using the closed system method, and then using the data to estimate the model parameters of the respiration model proposed by Lee et al.(1991). The respiration model is a Michaelis-Menten enzyme kinetics type equation

$$\frac{V_m[O_2]}{K_m+(1+[CO_2])/K_i[O_2]} \qquad (2)$$

where r is the respiration rate; V_m, K_m and K_i and K_i are adjustable parameters. $[CO_2]$ is CO_2 concentration, and $[O_2]$ is O_2 concentration. Equation (2) is applicable to both the O_2 consumption rate and the CO_2 evolution rate. If R. Q≠1, each respiration rate requires a different set of parameter values. Equation (2) has the advantages of requiring less parameters and being somewhat mechanistic, compared to those purely empirical equations reported in the literature. Once the model parameters are estimated, respiration as a function of O_2 concentration and CO_2 concentration may be estimated with Equation (2). The temperature dependence of respiration rate may be assumed to follow an Arrhenius type equation.

Mathematical Model and Package Requirements

After obtaining the optimum gas composition and the respiration rate, mathematical models may be used to determine the package requirement. A simple model to design MAP for steady state consists of two mass balances, one for O_2 and the other for CO_2. The effect of nitrogen on respiration rate is assumed to be negligible. In these mass balances, the efflux rate of CO_2 through the package is equated to the CO_2 evolution rate of the produce, and the influx rate of O_2 through the package is equated to the O_2 consumption rate of the produce, as follows:

$$CO_2\ \text{evolution}: Eco_2\ W=\frac{\overline{P}co_2 A}{\ell}(P_i, co_2-P_e, co_2) \qquad (3)$$

$$O_2\ \text{consumption}: Ko_2\ W=\frac{\overline{P}o_2 A}{\ell}(P_e, o_2-P_i, o_2) \qquad (4)$$

where

Eco_2 = evolution rate of CO_2

Ko_2 = consumption rate of O_2

$\overline{P}co_2$ = permeability to CO_2

$\overline{P}o_2$ = permeability to O_2

P_i, co_2 = internal CO_2 vapor pressure

P_e, co_2 = external CO_2 vapor pressure

P_i, o_2 = internal O_2 vapor pressure

P_e, o_2 = external O_2 vapor pressure

W = weight of produce

A = area of package

ℓ = tickness of package

There are altogether 11 variables in Equations (3) and (4). P_i, co_2 and P_i, o_2 are the optimum gas composition, Eco_2, and Ko_2 are the respiration rates, and these four variables may be determined experimentally as described above. The two environmental variables P_e, co_2 and P_e, o_2 may be assumed to be 0 and 0.21 atmophere, respectively. When three of the five remaining variables are specified, and the last two variables are determined by Equations (3) and (4).

A major difficulty in designing MAP for fresh produce is to find proper permeable films to satisfy the requirement for $\overline{P}co_2$ and $\overline{P}o_2$. Because there are many varieties of produce, a wide range of permeabilities is required. High permeabilities are required for rapidly respiring produce, and low permeabilites are required for slowly respiring produce. The permeabilities of some of the common food packaging plastic films are listed in Table 1. Although the table appears to include a larege selection for $\overline{P}co_2$ or $\overline{P}o_2$, the selection for a given combination of $\overline{P}co_2$ and $\overline{P}o_2$ is more limited. The permeability ratio $\overline{P}co_2/\overline{P}o_2$ is within a narrow range between 3 to 6.

Dividing Equation (3) by (4),

$$\frac{Eco_2}{Ko_2}=\frac{\overline{P}co_2}{\overline{P}o_2}\,\frac{(P_i, co_2-P_e, co_2)}{(P_e, o_2-P_i, o_2)}=\frac{\overline{P}co_2}{\overline{P}o_2}\,\frac{(P_i, co_2-0)}{(0.21-P_i, o_2)} \qquad (5)$$

and rearranging Equation (5), we obtain

$$P_i, co_2=\frac{R.Q.}{\beta}(0.21-P_i, o_2) \qquad (6)$$

$$\text{where R. Q.} = \frac{E_{CO_2}}{K_{O_2}} \tag{7}$$

$$\beta = \frac{\overline{P}_{CO_2}}{\overline{P}_{O_2}} \tag{8}$$

For constant R. Q. and β, Equation (6) shows that a plot of P_i, co_2 cersus $(0.21-P_i, o_2)$ yields a straight line. In Figures 2 and 3, lines of Equation (6) are plotted for $\beta=0.8$ and 5.0, assuming R. Q.$=1$. Such lines are useful for quickly identifying which commodities are potentially suitable for a particular film. In Figure 2 for example, celery, cauliflower, cabbage, and pepper require a β of 5.0, suggesting that low density polythylene (LDPE) is a potential film. However, the values of $\overline{P}_{CO_2}$ and $\overline{P}_{O_2}$ must also be calculated using Equations (3) and (4) for each of these commodities before concluding if the film is indeed applicable to that commodity.

Equations (3) and (4) are good design equations for estimating the package requirement at steady state. In passive modification, the initial period is at unsteady state during which the CO_2 concentration and O_2 concentration inside the package, and the respiration of the produce are changing with time. This unsteady state period may be discribed by the two ordinary differential equations of Hayakawa et al.(1975):

$$\frac{d[O_2]}{dt} = 100\left(\frac{A\,\overline{P}_{CO_2}\,(0.21-[O_2]/100)}{V\,\ell} - \frac{WK_{O_2}}{V}\right) \tag{9}$$

$$\frac{d[CO_2]}{dt} = 100\left(\frac{A\,\overline{P}_{O_2}\,(0.0-[CO_2]/100)}{V\,\ell} + \frac{W\,E_{CO_2}}{V}\right) \tag{10}$$

where V is the package free volume, and t is time. The initial conditions are usually specified as $[CO_2]=0$ and $[O_2]=0.21$ atm.

Research Needs

Listed below are some research needs for the development of MAP for fresh produce.

1. Research is needed to develop inexpensive films, especially edible or biodegradable films, that are suitable for MAP for fresh produce. Presntly the choices of films with suitable $\overline{P}_{CO_2}$ and $\overline{P}_{O_2}$ to control CO_2 and O_2 for MAP are rather limited. A way to overcome this limitation is to place absorbers or scavengers (Labuza, 1989) in either the primary or the secondary package to control CO_2 and O_2 levels. There is also recent work on studying the use of innovative films, such as ceramic filled polythylene, for MAP for fresh produce.

There is a need to develop films with temperature sensitivity closely match those of fresh produce. The film permeabilities of packaging films are much less sensitive than the respiration of fresh produce to temperature changes. During distribution and storage, temperature fluctuations could shift the gas composition in the package far away from its optimum range, perhaps even beyong its safety limits. Presently research is being conducted in developing side-chain crystallizable polymer fils that have higher temperature sensitivity to overcome this problem.

2. Research is needed to develop effective and inexpensive ways to control the relative humidity in modified atmosphere packages. The optimum relative humidity for storing fresh produce is generally between 85 to 95%. Higher (saturation or near saturation)relative humidities often result in growth of molds and bacteria. Recently work has been done on studying the use of in-package water absorbing compounds to maintain a target relative humidity.

Because the relative humidity in the package is affected by the transpiration rate of produce, there is also work on developing mathematical models to describe transpiration rate as a function of CO_2 and O_2.

3. Research is needed to better understand the intrinsic factors such as variety and picking date on respiration, skin and flesh resistance to gas diffusion, etc.

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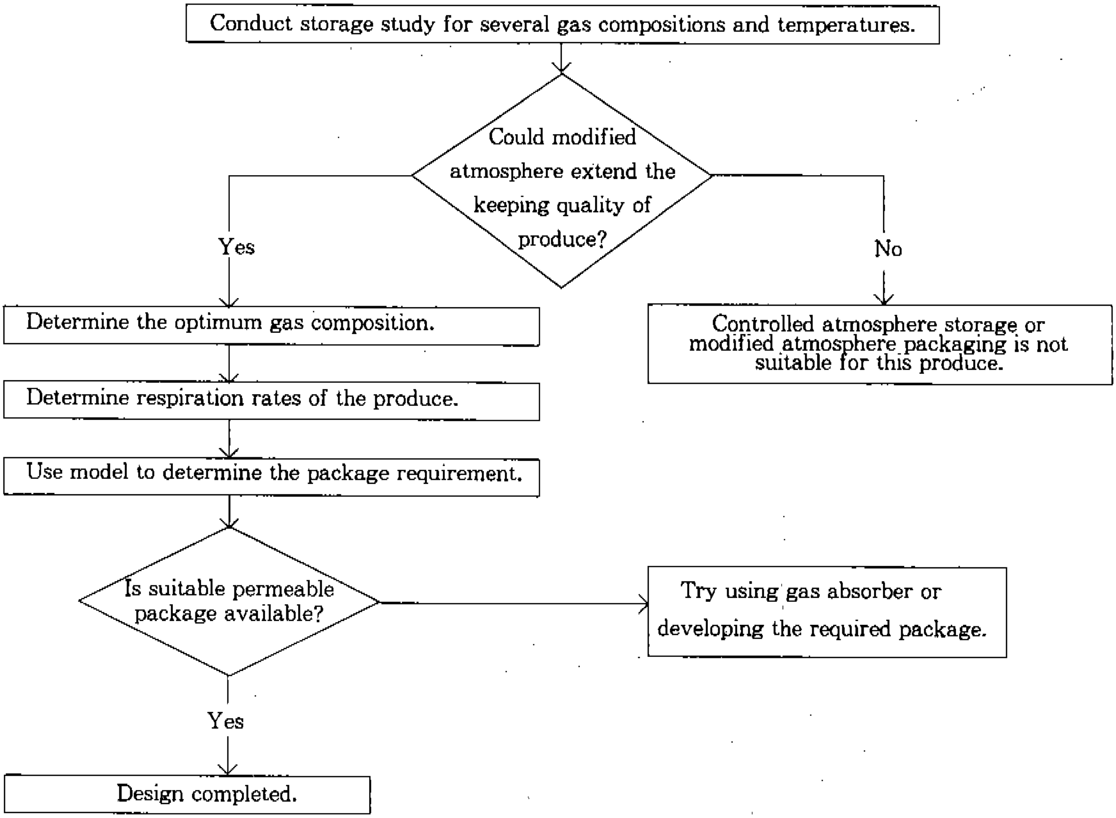

Figure 1. Flow Chart for Designing MAP for Fresh Produce

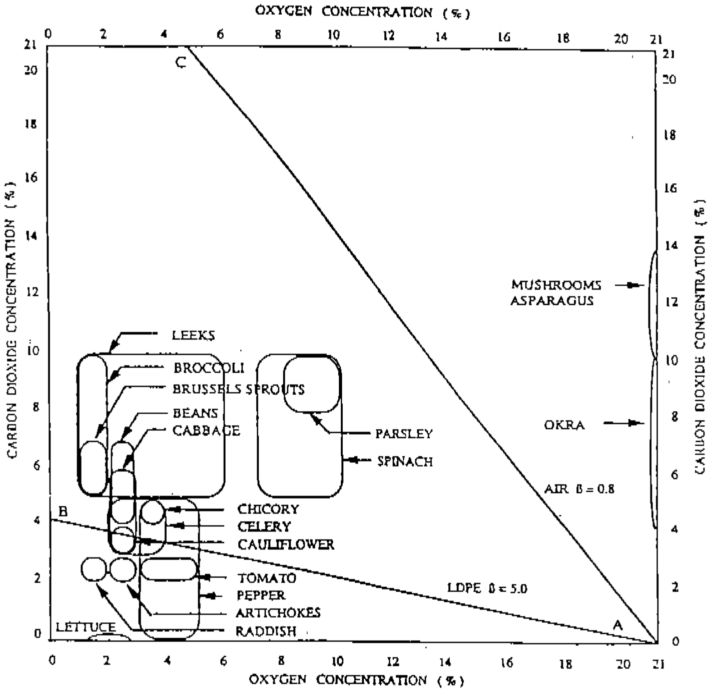

Figure 2. Optimum modified gas compositions for storage of vegetables. Form Mannapperuma et al. (1989)

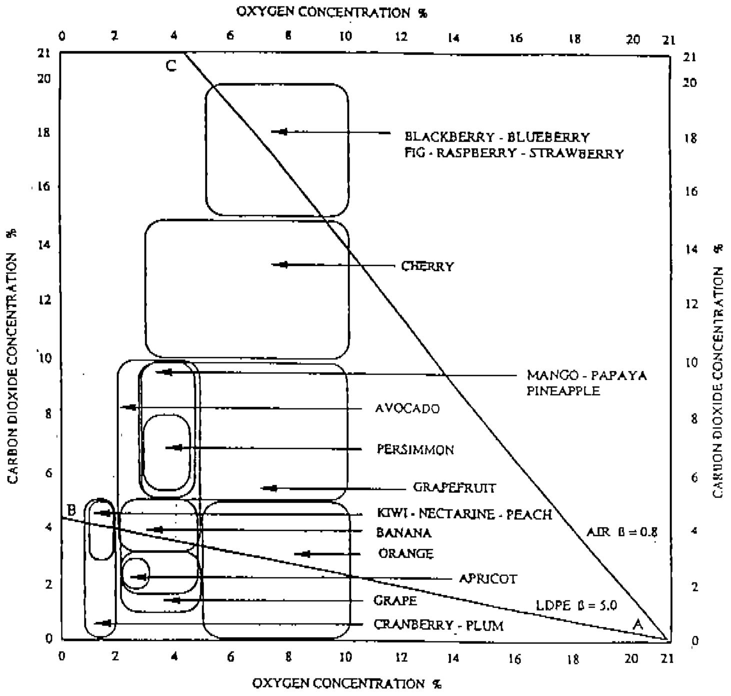

Figure 3. Optimum modified gas compositions for storage of fruits. From Mannapperuma et al.(1989)

Table 1. Typical Gas Permeability Values for Common Packaging Plastics

	Gas Permeability, $\frac{\text{cc mil}}{100\ \text{in}^2\ \text{day atm}}$		$\frac{\bar{P}co_2}{\bar{P}o_2}$
Plastics	$\vec{P}o_2$	$\vec{P}co_2$	
Polyethylene			
Low density	500	2900	5.8
High density	185	580	3.2
Polypropylene	200	650	3.3
Polystyrene	300	900	3.0
Polyvinyl chloride	5	20	4.0
Polyethyene terephthalate	5	24	4.8
Ceramic-filled LDPE	680	2460	3.6