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The Role of Packaging Film Permselectivity in Modified Atmosphere Packaging

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Modified atmosphere packaging (MAP) is commercially used to increase the shelf life of packaged produce by reducing the produce respiration rate, delaying senescence, and inhibiting the growth of many spoilage organisms, ultimately increasing product shelf life. MAP systems typically optimize O_2 levels to achieve these effects while preventing anaerobic fermentation but fail to optimize CO_2 concentrations. Altering film permselectivity (i.e., β, which is the ratio of CO_2/O_2 permeation coefficients) could be utilized to concurrently optimize levels of both CO_2 and O_2 in MAP systems. We investigated the effect of modifying film permselectivity on the equilibrium gas composition of a model MAP produce system packaged in containers incorporating modified poly(ethylene) ionomer films with CO_2/O_2 permselectivites between 4−5 and 0.8−1.3. To compare empirical to calculated data of the effect of permselectivity on the equilibrium gas composition of the MAP produce system, a mathematical model commonly used to optimize MAP of respiring produce was applied. The calculated gas composition agreed with observed values, using empirical respiration data from fresh cut apples as a test system and permeability data from tested and theoretical films. The results suggest that packaging films with CO_2/O_2 permselectivities lower than those commercially available (<3) would further optimize O_2 and CO_2 concentration in MAP of respiring produce, particularly highly respiring and minimally processed produce.

KEYWORDS: Ionomer films; CO_2 and O_2 permeability; CO_2/O_2 permselectivity; modified atmosphere packaging; packaging films

INTRODUCTION

Oxygen and CO_2 concentrations in modified atmosphere packaging (MAP) change as a function of produce respiration rate, temperature, and the area, thickness, and O_2 and CO_2 permeability coefficients of the packaging material (*1*). Several models, which combine these variables, have been published (*2*−*4*). Lakakul et al. (*4*), for example, have provided a detailed model of the effects of a wide variety of factors, including temperature, product mass, permeability, activation energy, and film type, area, and thickness on O_2 content in hermetically sealed packages containing apple slices. While quite useful, this work did not consider the effects of film permselectivity on both CO_2 and O_2 concentration. The concentration of both CO_2 and O_2 influence product quality. High barrier films can lead to anaerobic conditions and excessive CO_2 buildup, while low barrier films can result in less than optimal CO_2 concentrations, a condition which may not provide maximum shelf life extension, especially for rapidly respiring produce, such as minimally processed fruits and vegetables (*5*). Zhu et al. (*6*) used a second-order expression to demonstrate the importance of both O_2 consumption and CO_2 production on the respiration of rutabaga; however, they did not include the effects of package permeability in their otherwise excellent model.

The CO_2/O_2 permselectivity is defined as the ratio of CO_2 to O_2 permeation coefficients of the film (referred to as β). Commercial packaging films typically have CO_2/O_2 permselectivities of 4−8 (*7*). This ratio may be larger than optimal, and permselectivity may be a limiting factor for certain MAP applications. Therefore, our objective was to investigate the influence of CO_2/O_2 film permselectivity on MAP applications; empirical data was compared to that obtained from a widely cited respiration mathematical model. Packaged apple slices were used as a typical model of a rapidly respiring produce system. While variability in respiration rates does exist between different produce items, we believe that the underlying principles apply to permselectivity in general; thus, we selected one produce item to use as a model respiration system. We also used a glass package, with a polymeric film insert. The CO_2/O_2 film permselectivity was 1, and we assumed that no pressure differential was created across the barrier as individual gases permeate.

As described by Exama et al. (*8*), the transient O_2 level as a function of time can be expressed by ordinary differential equations (ODE)

$$\mathrm{dyiO_2}/\mathrm{d}t = (AP_{O_2}p/VL)(\mathrm{yeO_2} - \mathrm{yiO_2}) - (WR_{O2}/V) \quad (1)$$

where A = area of permeable film, P_{O_2} = O_2 permeability coefficient, p = pressure (1 atm), V = free volume of the

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Table 1. Apple Slice Mass, Package Free Volume, and Ionomer Film Permeability and Permselectivity (determined at ambient temperature) Used to Experimentally Determine Changes in Gas Composition in Cut Apples Stored in Glass Jars Covered with Each of Three Ionomer Films (n = 3 for each film)[a]

material	film area (cm^2)	film thickness (cm)	apple slice wt (Kg)	container free vol mL)	(ml cm/cm^2s cmHg) P_{O2}	P_{CO_2}	P_{CO_2}/P_{O_2}
ionomer A	7.9	0.0082	0.0173	230	5.27×10^{-9}	4.45×10^{-9}	0.85
ionomer B	7.9	0.0072	0.0178	229	2.03×10^{-9}	2.65×10^{-9}	1.29
ionomer C	7.9	0.0075	0.0120	236	3.11×10^{-9}	3.33×10^{-9}	1.07

[a] Experimental and calculated results are given in **Figure 1**.

package, L = film thickness, yeO_2= external (atmospheric) O_2 concentration (21%), yiO_2 = internal O_2 concentration (%), W= weight of produce, and R_{O_2} = O_2 consumption rate.

To model the O_2 composition in a package according to eq 1, the respiration rate (R_{O2}) must first be modeled by assuming that respiration rate is a function of O_2 concentration, that CO_2 concentration has no direct effect on respiration rate, and that the respiration quotient (RQ), or ratio of the rate of CO_2 produced to the rate of O_2 consumed, is 1. Several such models have been published. We chose the model published by Lee et al. (*9*), because it is the most widely cited. Their model is based on Michaelis−Menten kinetics for O_2 consumption as follows:

$$R_{O_2} = \frac{\mathrm{Vm}[O_2]}{\mathrm{Km} + [O_2]}$$

where R_{O_2} = respiration rate (mL Kg^{-1} h^{-1}), Vm = maximum respiration rate (mL Kg^{-1} h^{-1}), $[O_2]$= oxygen concentration (%), and Km = Michaelis−Menten constant.

It follows that

$$R_{CO_2} = \mathrm{RQ}R_{O_2} \tag{3}$$

Because it is assumed that RQ = 1, $R_{CO_2} = R_{O_2}$, and eq 1 can be rewritten as

$$(dyiO_2/dt) = (AP_{O_2}p/VL)(yeO_2 - yiO_2) - (w/v)((\mathrm{Vm}[O_2])/(\mathrm{Km} + [O_2])) \tag{4}$$

The change in gas composition inside any given flexible package of specific dimension (i.e., surface area) made from a permeable film can be mathematically simulated once the solution to eq 4 is obtained. The O_2 level at a given time in a package (y_{O_2}) is therefore

$$y_{O_2}(t) = \int(dyiO_2/dt) = \int[(AP_{O_2}p/VL)(yeO_2 - yiO_2) - (W/V)(\mathrm{Vm}[O_2]/(\mathrm{Km} + [O_2]))] \tag{5}$$

Similarly, an equation can be developed to calculate values of CO_2 concentration over time. With the numerical solutions for the ODEs for both O_2 and CO_2, simulation of the internal atmosphere of a given MAP application with permeable flexible materials can be achieved. Although the respiration quotient can be affected by several environmental parameters, including both O_2 and CO_2 concentration, we assumed an RQ of unity; our objective was to demonstrate the effect of permselectivity on equilibrium atmosphere, not the effect of the respiration quotient.

Our research objective was to determine the role of packaging film permselectivity in modified atmosphere packaging by (1) experimentally measuring the effect of modifying film permselectivity on the equilibrium gas composition of a model MAP produce system packaged in containers incorporating flexible modified poly(ethylene) ionomer films and (2) comparing empirical to calculated data of the effect of permselectivity on the equilibrium gas composition of the MAP produce system, applying an ODE incorporated into a mathematical model commonly used to optimize modified atmosphere packaging (MAP) of respiring produce.

MATERIALS AND METHODS

Respiration Rate of Cut Apples. Red delicious apples at climacteric peak were obtained from Cornell Orchards (Ithaca, NY). Individually cleaned apples were cored, peeled, and sliced into eight equal wedges. Any softened or brown parts were discarded. The respiration rate of cut apples was measured by the method of Lee (*10*), in which a closed system is used. Apple wedges (83.5−91.4gm) were placed in 250-mL airtight glass jars sealed with metal lids fitted with silicone-sealed rubber septa as sampling ports and held at 23 °C. Initially, the jars contained air; the change in gas composition over time was monitored by headspace analysis. Headspace gas samples (0.5 mL) were withdrawn by gastight syringe and analyzed by gas chromatography/thermal conductivity detector for CO_2 and O_2 as described by Gunes et al. (*5*). Three jars were used for each respiration measurement, and sampling terminated when O_2 levels declined to <2%. Only the initial linear portion of the curves was used to calculate respiration rates to minimize any effects of changing internal pressure due to respiration.

Package Model. Apple slices were prepared, weighed, and placed in glass jars as above, using a different lid system. Metal lids were prepared with single 7.9-cm diameter holes in the center, which were then covered with test films; films were sealed in place along the periphery with epoxy. Thus, a known “package” permeation rate could be calculated based on the area of the hole and permeation rate of the film (*11*). Apple wedges were immersed in water and the change in volume noted to estimate volume. Density was calculated to give the free volume of each jar. Characteristics and dimensions of the slices and the package are shown in **Table 1**. Ionomer films with different permselectivities (**Table 1**) were formed from ethylene/methacrylic acid ionomer (sodium ion; Scientific Polymer Products, Inc; Ontario, NY, Cat# 465) as described by Al-Ati and Hotchkiss (*12*) (2002). The gas transmission rates (**Table 1**) were determined as described by Al-Ati and Hotchkiss (*12*). Headspace analysis film permeability was carried out as described above. All experiments were independently repeated three times.

To simplify the calculation of Michaelis−Menten parameters, eq 2 was rewritten as

$$\frac{1}{R_{O_2}} = \frac{1}{\mathrm{Vm}} + \left(\frac{\mathrm{Km}}{\mathrm{Vm}}\right)\left(\frac{1}{[O_2]}\right)$$

A linear regression plot of ($1/R_{O_2}$) against ($1/[O_2]$) thus generated a line with a slope equal to (Km/Vm) and an intercept equal to (1/Vm).

RESULTS AND DISCUSSION

The rate of O_2 consumption (R_{O_2}) of the apple slices was calculated as

$$R_{O_2} = \frac{\Delta[O_2]V}{W\Delta t} \tag{7}$$

where V is free volume (ml), W is the weight of the apple slices (Kg), and $\Delta[O_2]$ is the change in O_2 level (%) over a period of time Δt (hours).

Vm and Km were found to be 56.8 mL/Kg hr and 23.4%, respectively ($R^2 = 0.91$). The respiration rate for the apple slices was

$$R_{O_2} = \frac{56.8[O_2]}{23.4 + [O_2]} \tag{8}$$

To model the effect of $[O_2]$ on CO_2 production, $\%O_2$ was plotted against $\%CO_2$. A linear regression of the plot generated a straight-line equation

$$\%O_2 = -0.9781(\%CO_2) + 0.222,\ R^2 = 0.999 \tag{9}$$

When the assumption that RQ = 1 is used, $[O_2]$ in eq 8 can be expressed in terms of $[CO_2]$. The CO_2 production rate gave the following model:

$$R_{CO_2} = \frac{56.8((-0.9781)([CO_2]) + 0.222)}{23.4 + ((-0.9781)([CO_2]) + 0.222)} \tag{10}$$

These empirically based respiration models (8 and 10) were used to estimate the O_2 levels and CO_2 generated by apple slices inside a film package, as discussed below.

Modeling of headspace changes in MAP was possible with the incorporation of the respiration models into the ODEs, the solution of which generates calculated values of the O_2 and CO_2 levels over time, inside the particular flexible packaging system under investigation. The $\%O_2$ change over time can be calculated by substituting eq 8 into eq 1 to give

$$\mathrm{d}yiO_2/\mathrm{d}t = (AP_{O_2}p/VL)(21.0 - yiO_2) - (W/V)\left(\frac{56.8(yiO_2)}{23.4 + (yiO_2)}\right) \tag{11}$$

Similarly, the following ODE simulates CO_2 production rate inside the proposed package:

$$\mathrm{d}yiCO_2/\mathrm{d}t = (AP_{CO_2}p/VL)(0 - yiCO_2) + (W/V)\left(\frac{56.8((-09781)(yiCO_2) + 0.222)}{23.4 + ((-0.9781)(yiCO_2) + 0.222)}\right) \tag{12}$$

Calculation of the changes in $[O_2]$ and $[CO_2]$ due to respiration and package permeation was achieved by determining the numerical solutions of eqs 11 and 12 using the Runge−Kutta method (MATLAB Release 12, The MathWorks Inc., MA).

Experimentally determined values (**Table 1**) closely matched the calculated values (**Figure 1)** for CO_2 and O_2 concentration from apple slices placed in jars sealed with each of three ionomer films. Apple slices placed in test containers sealed with ionomer films resulted in reduced O_2 levels, which may be advantageous for fresh-cut fruits, yet left sufficient O_2 to prevent anaerobic respiration. The empirical steady-state level of O_2 for three different ionomer films was 1.6, 3.0, and 4.1% (**Figure 1**). The CO_2 accumulated inside the jars reached 23.3, 22.5, and 19.1% for the three films. Similar reduced $[O_2]$ and elevated $[CO_2]$ have been shown to be beneficial for fresh cut apples stored at 5 °C (*5*).

The model was used to estimate the effects of changing package dimension, product weight, and free volume on atmosphere composition. The model was also used to compare the CO_2 and O_2 levels generated by cut apples packaged using ionomer film A with three common polymers (low-density polyethylene (LDPE), poly(vinylidene chloride) (PVdC), and silicon rubber) using standardized package and film parameters (**Table 2**). Permeation coefficients were taken from literature values compiled by Al-Ati and Hotchkiss (*7*). LDPE was evaluated because of its commercial importance, and PVdC and silicon rubber were evaluated because they represent two extremes in gas permeability coefficients. PVdC is one of the highest gas barrier materials used for food packaging, and silicon rubber is a very poor gas barrier. The difference in gas permeability coefficients between the two materials is 5 orders of magnitude. Therefore, untested common polymeric films would be expected to generate CO_2 and O_2 levels that lie between the gas levels provided by PVdC and silicon rubber.

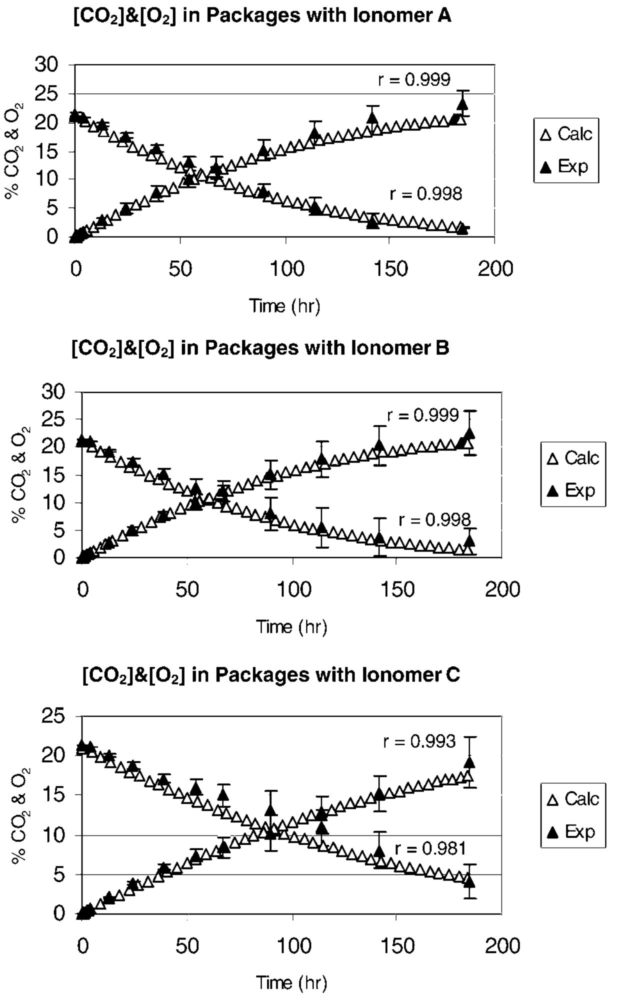

Figure 1. Theoretical (i.e., calculated) (△) versus experimentally determined (▲) O_2 and CO_2 concentrations (± sd) inside packages made from ionomer films A, B, and C (see **Table 1**; $n = 3$ for each ionomer). At time 0 h, O_2 level was 21%, and CO_2 level was 0%.

LDPE was calculated to result in a low O_2 concentration (0.13%), which raises concern that anaerobic fermentation would occur if apples slices were sealed in this film (**Figure 2**). Silicon rubber resulted in higher O_2 levels (5%) but low CO_2 levels (6.7%). The combination of the low O_2 permeation rate of PVdC and apple slice respiration resulted in anaerobic conditions (0% O_2) while the CO_2 accumulated to 22.7% (**Figure 2**). The time to reach equilibrium varied from 5 to 10 h. While the PVdC theoretical model produced acceptable CO_2 levels for fresh-cut apples, it failed to provide O_2 levels needed to maintain aerobic respiration. Of the films evaluated in these calculations, only ionomers in which the permselectivity had been modified (**Table 1**) produced both acceptable O_2 (2%) and CO_2 (21%) levels. If the same cut apple mass and film areas were used, common polymeric films with permeability coefficients between PVdC and silicon rubber would likely result in O_2 levels between that of PVdC (0%) and silicon rubber (5%); CO_2 levels would be between 6.7 and 23%, provided by silicon rubber and PVdC films, respectively.

Parameters used to calculate the theoretical gas composition in packages made from ionomer A and LDPE with different CO_2/O_2 permselectivities are given in **Table 3**. Parameters used to calculate the effect of package dimension and product mass on theoretical gas composition in packages made from an ionomer film with O_2 and CO_2 permeability coefficients of 5.27×10^{-9} and 4.45×10^{-9} mL cm/cm^2 s cm Hg are given in **Table 4**. The calculated effect on equilibrium

Table 2. Package and Film Parameters Used to Calculate Theoretical CO_2 and O_2 Concentrations in Apple Slices in Theoretical Packages Made from Ionomer A, LDPE, PVdC, and Silicon Rubber Films at 23 °C ($n = 3$, ± Sd)[a].

material	area cm^2	apple weight (Kg)	free vol (ml)	thickness (cm)	mL cm/ cm^{2}s cmHg PO$_2$	PCO$_2$
ionomer A	360	0.1	50	0.00254	$5.27 \times 10^{-9} \pm 0.0$	$4.45 \times 10^{-9} \pm 0.0$
LDPE	360	0.1	50	0.00254	2.88×10^{-10}	1.26×10^{-9}
silicon rubber	360	0.1	50	0.00254	1.24×10^{-8}	6.62×10^{-8}
PVdC	360	0.1	50	0.00254	3.30×10^{-13}	1.98×10^{-12}

[a] Results are given in **Figure 2**.

Table 3. Parameters Used to Calculate Theoretical Gas Composition in Packages Made from Ionomer A and LDPE with Different (adjusted) CO_2/O_2 Permselectivities[a]

material	area (cm^2)	weight (Kg)	free vol (ml)	thickness (cm)	mL cm/cm^{2}s cmHg PO$_2$	PCO$_2$
unmodified ionomer	360	0.1	50	0.00254	5.27×10^{-9}	4.45×10^{-9}
ionomer with decreased CO_2 barrier	360	0.1	50	0.00254	5.27×10^{-9}	2.31×10^{-8}
ionomer with increased O_2 barrier	360	0.1	50	0.00254	1.02×10^{-9}	4.45×10^{-9}
unmodified LDPE	360	0.1	50	0.00254	2.88×10^{-10}	1.26×10^{-9}
LDPE with increased CO_2 barrier	360	0.1	50	0.00254	2.88×10^{-10}	2.88×10^{-10}
LDPE with decreased O_2 barrier	360	0.1	50	0.00254	1.26×10^{-9}	1.26×10^{-9}

[a] Results Are Given in **Figure 3**.

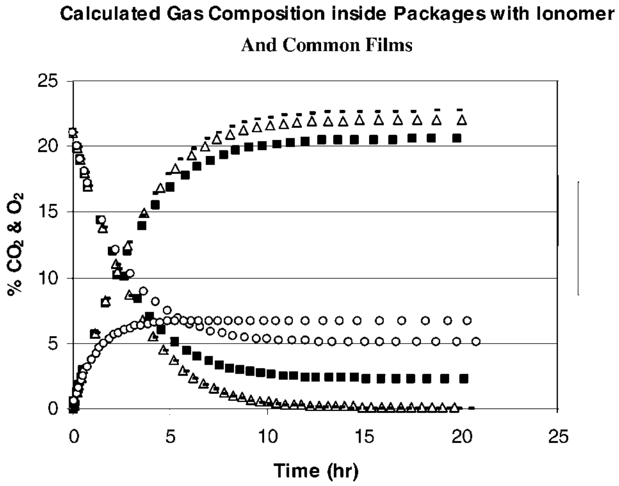

Figure 2. Theoretical (i.e., calculated) O_2 and CO_2 concentrations inside packages made from ionomer film A (■), LDPE (△), PVdC (—), and silicon rubber (○) films.

Table 4. Parameters Used to Calculate the Effect of Package Dimension and Product Mass on Theoretical Gas Composition in Packages Made from an Ionomer Film[a,b]

area cm^2	weight (Kg)	free vol (ml)	thickness (cm)
360	0.1	50	0.00254
720	0.1	50	0.00254
360	0.1	25	0.00254
360	0.1	50	0.00127
360	0.05	50	0.00254

[a] Results are given in **Figure 4**. [b] Ionomer film had O_2 and CO_2 permeability coefficients (mL cm/cm^2 s cmHg) of 5.27×10^{-9} and 4.45×10^{-9}, respectively.

CO_2 and O_2 concentration inside a theoretical package resulting from changes in film permeability and permselectivity is expressed graphically in **Figure 3**; equilibrium effects due to changes in film area, product mass, and free volume are expressed in **Figure 4**. For ionomer A, the calculated O_2 and CO_2 concentrations at steady state were 2.3 and 20.5%, respectively, and were reached in approximately 10 h (**Figure 3**, parts A and B). Free volume would not be expected to effect steady-state gas composition, but when the free volume was reduced from 50 to 25 mL, the rate at which gas composition approached steady state was reduced from 18 to 9 h (**Figure 4**). However, changing the free volume did not change the calculated steady-state levels of the gases (2.3% for O_2 and 20.5% for CO_2). Minimizing the free volume would facilitate reaching the steady-state faster, which may be advantageous for fresh-cut produce.

Reducing the thickness of ionomer A from 1 to 0.5 mil had a similar effect on the [CO_2] and [O_2] to that resulting from doubling the film area from 360 cm^2 to 720 cm^2 (**Figure 4**). The calculated [O_2] and [CO_2] at steady state were 4.4 and 18.5% and was reached in approximately 10 h. Reduction in film thickness did not change the time required to reach equilibrium but increased the [O_2] from 2.3 to 4.4%, and reduced the [CO_2] from 20.5 to 18.5%. Increasing the film area increased the amount of gas permeating through the film. Therefore, the film would allow more O_2 into the package (thus increasing the [O_2] at steady state) and allow more CO_2 to escape out of the package (thus reducing the [CO_2] at steady state).

Reducing the weight of apple slices from 100 to 50 g also led to the same steady-state [CO_2] (18.5%) and [O_2] (4.4%) as reducing film thickness by one-half or by doubling the film area. However, it would take about 40 h to reach the steady state, which is twice the time required for 100 g of slices to reach steady state.

These modeled results indicate that changing the free volume affects the time required for [CO_2] and [O_2] to reach steady state, but does not affect the steady-state levels of both gases. Reducing the film thickness by 1/2 or doubling the area changed the steady-state levels of the gases but not the time required for steady state. Packages with half the apple slice weight required twice the time to reach steady state. From a package design perspective, if the time to reach steady state must be shortened, then reducing the free volume or increasing the produce weight should be considered. However, changing the produce weight changes the gas concentrations, whereas changing the free volume does not. When the O_2 levels provided by a given package are close to anaerobic conditions, increasing the film area or reducing the film thickness, or a combination of the two should be considered. In this case, the time required to reach steady state would not be changed. Such manipulations are only successful when the gas permeability coefficients of the packaging materials are such that they provide concentrations of CO_2 and O_2 that are reasonably close to the desired values. For example, neither PVdC or silicon rubber would provide reasonable gas levels with commercially feasible produce weights, film areas, thickness, or free volumes.

The effect of film CO_2/O_2 permselectivity can be estimated by calculating the equilibrium gas composition with different permeability

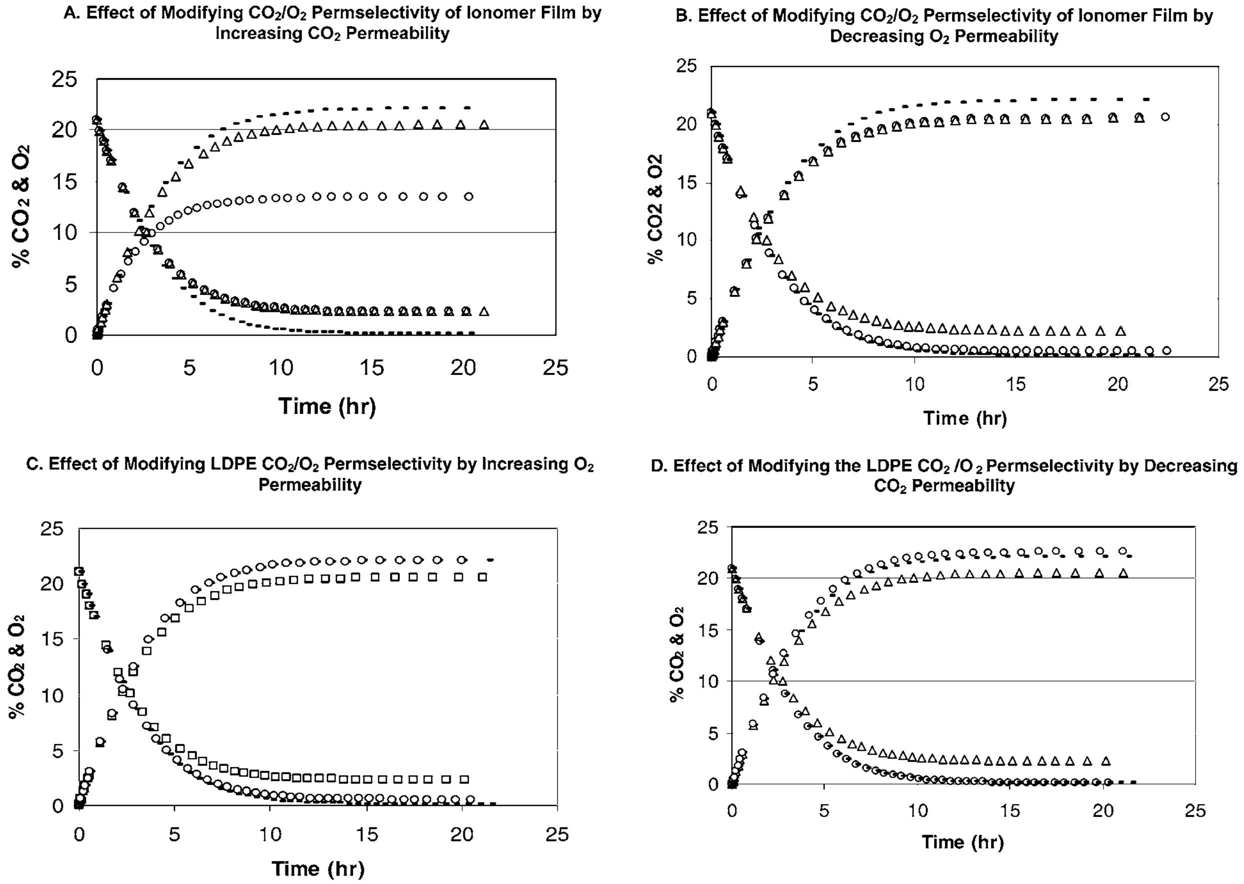

Figure 3. Theoretical (i.e., calculated) effect on gas composition of increasing CO_2 permeability (○) (A and B) or decreasing O_2 permeability (○, △) (Figures 3C & D) compared to packages made from unmodified ionomer (ρ), or LDPE (—) films.

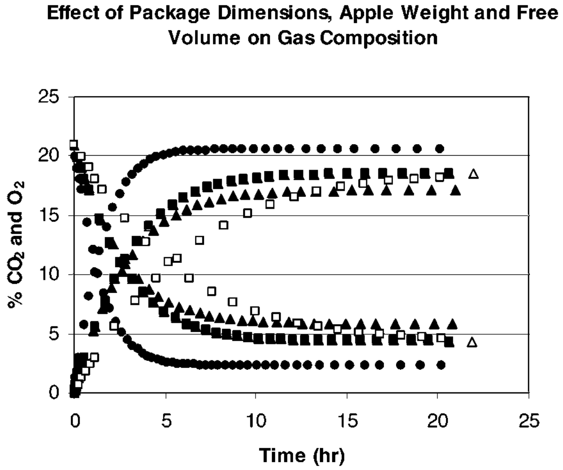

Figure 4. Effect of changing packaging dimensions, free volume, or product mass on the theoretical (i.e., calculated) gas composition inside packages made from ionomer film A (**Table 1**). Film area = 360 cm^2, apple slices weight = 0.1 Kg, free volume = 50 mL, and film thickness = 0.00254 cm (▲); film area increased to 720 cm^2 (△); free volume reduced to 25 mL (●); film thickness reduced to 0.00127 cm (■); apple slice weight reduced to 0.05 Kg (□).

coefficients (**Table 3**; **Figure 3**). For example, LDPE would be expected to generate a low [O_2] (0.13%) and high [CO_2] (22.1%) (**Figure 3A**). Ionomer films with a permselectivity of 0.844 (**Table 3**) would be expected to result in 2.3% [O_2] and 20.6% [CO_2] at equilibrium in the same system. Adjusting the CO_2 permeability coefficient of the ionomer to 2.31×10^{-8} (mlcm/cm^2 sec cm Hg) while keeping the O_2 permeability coefficient the same (**Table 3**), would give a permselectivity equal to that of LDPE (i.e., 4.4) and would result in a decrease in [CO_2] from 22.1 to 13.5% (**Figure 3A**). Alternatively, decreasing the O_2 permeability of the ionomer to 1.02×10^{-9} (mlcm/cm^2 sec cm Hg) decreases the [O_2] from 2.3 to 0.45% (**Figure 3B**), which may result in anaerobosis.

If the CO_2 permeability of LDPE were theoretically decreased from 1.26×10^{-9} (mlcm/cm^2 sec cm Hg) to match that of O_2 (2.88×10^{-10} mlcm/cm^2 sec cm Hg), the CO_2 concentration would increase slightly from 22.1 to 22.5% (**Figure 3C**), and the [O_2] would remain low (0.13%). If the O_2 permeability of LDPE were increased to 1.26×10^{-9} (mlcm/cm^2 sec cm Hg) (**Table 3**), the O_2 concentration would increase from 0.13 to 0.6% (**Figure 3D**). The adjusted LDPE would be expected to provide more O_2 and would, therefore, be less likely to create anaerobic conditions, while maintaining a higher CO_2 concentration (22.1%).

Oxygen permeability may be a limiting factor for MAP of rapidly respiring fresh-cut produce, due to the creation of anaerobic conditions; therefore, changing CO_2/O_2 permselectivity by increasing O_2 permeability to match that of CO_2 would have the greatest benefit. Because [CO_2] as high as 25−30% may be desirable for fresh-cut fruits such as apples (*5*), it follows that CO_2 permeability should be kept low and O_2 permeability increased to match that of CO_2. Unfortunately, no such film is commercially available.

CONCLUSIONS

MAP of fresh-cut fruits and some vegetables face a technical hurdle, resulting from the failure of common packaging films to simultaneously provide optimal O_2 and CO_2 permeation rates (i.e., optimal CO_2/O_2 permselectivity). Package dimensions, produce weight, or free volume can be manipulated to reach a desirable level of either [O_2] or [CO_2], but not both. Commercial films can provide sufficient O_2 permeation to prevent anaerobic fermentation but sub optimal [CO_2]. Adjustment of CO_2/O_2 permselectivity to near unity would allow the internal atmosphere of fresh produce/package system to be optimized. Further, as others have pointed out (*4*), packaging dimensions, produce weight, and free volume can be manipulated to control the time needed to establish steady-state conditions. Because the respiration process and film permeability are both temperature dependent, changes in respiration rate due to temperature changes should be balanced by changes in film permeability to maintain the desired steady-state gas composition.

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