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Gas Diffusion Tube Dimension in Sensor-Controlled Fresh Produce Container System to Maintain the Desired Modified Atmosphere

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Abstract Modified atmosphere (MA) of reduced O_2 and elevated CO_2 concentrations has been used for keeping the quality of fresh produce and extending the shelf life. As a way to attain the beneficial MA package around the produce, a gas diffusion tube or perforation can be attached onto the container and controlled on real time in its opening/closing responding to O_2 and CO_2 concentrations measured by gas sensors. The timely-controlled opening of the gas diffusion tube can work in harmony with the produce respiration and help to create the desired MA. By use of the mathematical modeling, the effect of tube dimension on the controlled container atmosphere was figured out in this study. Spinach and king oyster mushroom were used as typical commodities for designing the model container system (0.35 and 0.9 kg in 13 L, respectively) because of their respiration characteristics and the optimal MA condition (O_2 7~10%/CO_2 5~10% for spinach; O_2 2~5%/CO_2 10~15% for mushroom). With a control logic for the gas composition to stay as close as possible to optimum MA window without invading injurious low O_2 and/or high CO_2 concentrations, the atmosphere of the sensor-controlled container could stay at its lower O_2 boundary or upper CO_2 limit under certain tube dimensional conditions. There were found to be the ranges of the tube diameter and length allowing the beneficial MA. The desired range of the tube dimension for spinach consisted of combinations of larger diameter and shorter length in the window of 0.3~2 cm diameter and 0.2~10 cm length. Similarly, that for king oyster mushroom was combinations of larger diameter and shorter length in the window of 0.9~2 cm diameter and 0.2~3 cm in length. Clear picture on generally affordable tube dimension range may be formulated by further study on a wide variety of commodity and pack conditions.

Keywords Modified atmosphere, Fresh produce, Sensor, Perforation, Control

Introduction

Modified atmosphere packaging (MAP) is a technique used for preserving the freshness of fresh produce and prolonging the shelf life by modifying the atmosphere surrounding the produce. The modified atmosphere (MA) in proper window is widely known and accepted to suppress the respiration, delay the ripening process and reducing the deterioration reaction, contributing to the quality preservation[1,2]. The atmosphere modification inside the package is achieved by the interplay between two processes, the respiration of the produce and the transfer of gases through the packaging film, which leads to an atmosphere of reduced O_2 and increased CO_2 concentrations[3,4]. While MA packages can attain the beneficial atmosphere relatively at lower cost compared to controlled atmosphere storage, their ability to create and maintain the optimum MA conditions is limited due to the limited range and characteristic of gas permeability of plastic packaging materials. As means to widen the applicability of MAP, high gas transfer devices such as micro-perforations or gas diffusion tubes have been tried for a variety of commodities[5,6]. Recently, as a more effective way to create the beneficial MA in package or container of fresh produce, an MA container equipped with gas sensors and gas diffusion tube controllable in its opening/closing has been suggested and tested for maintaining a desired gas composition[7]. It was reported that the gas composition of the properly designed container equipped with the diffusion tube could stay at the lower O_2 boundary or upper CO_2 limit of optimal MA helping the quality preservation. However, the ability to achieve the desired MA was reported to depend on tube dimension in a certain extent.

This study therefore aims to investigate the behavior of the container atmosphere depending on tube dimension variables to find their adequate ranges. The concept was tested at two typical commodities, spinach and king oyster mushroom for a commonly used temperature condition of 10°C. They were cho-

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sen because of typically different respiration characteristics and optimal MA conditions (O_2 7~10%/CO_2 5~10% for spinach; O_2 2~5%/CO_2 10~15% for king oyster mushroom)[3,8,9].

Materials and Methods

1. Model MA container system

A fresh produce container with a diffusion tube that can be opened or closed with linkage to O_2 and/or CO_2 sensors as reported by Jo et al.[7] was used as a model system for analysis. The container is equipped with O_2 and/or CO_2 gas sensors monitoring the gas concentrations on a real-time basis, and these concentrations are supplied to the control system as source information to regulate the opening/closing actuation of the diffusion tube. Mechanical mechanism such as solenoid value may be used for the opening/closing of the tube. A typical container structure consists of a 2-mm thick polypropylene box with dimension of 32×23×18 cm (≈ 13 L of volume), containing 0.35 kg of spinach or 0.9 kg of king oyster mushroom at 10°C. Different dimensions of gas diffusion were assumed to be attached on the container and tested in the resulting container atmosphere. Graphical presentation of the container concept can be found in the recent article by Jo et al.[7].

2. Mathematical model for container atmosphere simulation

Based on the analysis of Kwon et al.[10] a simplified diffusion model on the perforated produce package was used to simulate the container atmosphere depending on the tube dimension:

$$\frac{dn_{O2}}{dt} = \frac{ND_{O2}A(0.21p_a - p_{O2})}{L+\delta}\left(\frac{1}{RT}\right) + \frac{\bar{P}_{O2}S(0.21p_a - p_{O2})}{B} - WR_{O2} \tag{1}$$

$$\frac{dn_{CO2}}{dt} = \frac{ND_{CO2}A(0.00 - p_{CO2})}{L+\delta}\left(\frac{1}{RT}\right) + \frac{\bar{P}_{CO2}S(0.00 - p_{CO2})}{B} + WR_{CO2} \tag{2}$$

$$\frac{dn_{N2}}{dt} = \frac{ND_{N2}A(0.78p_a - p_{N2})}{L+\delta}\left(\frac{1}{RT}\right) + \frac{\bar{P}_{N2}S(0.78p_a - p_{N2})}{B} \tag{3}$$

where n_{O2}, n_{CO2} and n_{N2} are the respective mole number of O_2, CO_2 and N_2 gas in the container at time t (h); p_{O2}, p_{CO2} and p_{N2} are the respective partial pressure of O_2, CO_2 and N_2 gas in the container at time t; D_{O2}, D_{CO2} and D_{N2} are the respective diffusivities of O_2, CO_2 and N_2 gas in air (m^2 h^{-1}); N represents the state of the diffusion tube (1 when the tube is open and 0 when the tube is in close state), which has length L (m), diameter d (m) and cross-sectional area A (m^2); d is a correction term for the gas diffusion resistance in the tube (1.1d); B and S are the thickness (mm) and surface area (m^2) of the plastic layer (wall and cover), respectively; $\bar{P}_{O2}$, $\bar{P}_{CO2}$ and $\bar{P}_{N2}$ are the gas permeabilities of the polypropylene layer against O_2, CO_2 and N_2 (5.71×10^{-10}, 1.63×10^{-9} and 1.14×10^{-10} mol mm m^{-2} h^{-1} Pa^{-1} against O_2, CO_2 and N_2, respectively, at 10°C); p_a is the normal atmospheric pressure (p_a, 1.013×10^5 Pa); R is the ideal gas constant (8.314 J K^{-1} mol^{-1}); T is the temperature (K); W is the produce weight (kg); R_{O2} is the respiration rate of O_2 consumption (mol kg^{-1} h^{-1}); R_{CO2} is the respiration rate of CO_2 production (mol kg^{-1} h^{-1}). The first terms on the right-hand sides of Eqs. (1)~(3) represent gas diffusion through the tube based on Fick's law. The second terms on the right-hand sides of each equation describe the diffusive gas permeation through the plastic layer, and the last terms in Eqs. (1) and (2) describe the respiration.

In solving the Eqs. (1)~(3) for simulating the container atmosphere, N, the state of the diffusion tube is determined by the control logic for attaining the desirable MA[7]. When oxygen concentration ($[O_2]$) decreases up to its lower bound ($[O_2]_L$) of optimal MA window or carbon dioxide concentration ($[CO_2]$) increases up to its higher limit ($[CO_2]_H$) of optimal MA window, the diffusion tube as a device to increase gas transfer is turned on to the open position (N=1) from initially closed state and also respond the same way later in the storage: whenever gas concentration reaches the borderline ($[O_2]_L$ or $[CO_2]_H$), the control is made to open the valve for preventing it from entering the injurious zones (too low O_2 and/or too high CO_2 concentrations). While $[O_2]$ stays above $[O_2]_L$ and $[CO_2]$ is below $[CO_2]_H$, the tube may be controlled to simply close (N=0).

The respiration rate of the produce in Eqs. (1) and (2) was supplied as a function of the O_2 and CO_2 concentrations:

$$R_{O2} \text{ or } R_{CO2} = \frac{V_m p_{O2}}{K_m + (1 + p_{CO2}/K_i)p_{O2}} \tag{4}$$

where V_m, K_m and K_i are respiration model parameters. The respiration kinetic data for spinach and king oyster mushrooms at 10°C were adopted from Jo et al.[7]: V_m = 1.911 mmol kg^{-1} h^{-1}, K_m = 3.58 kPa and K_i = 22.4 kPa for the R_{O2} of spinach; V_m = 1.516 mmol kg^{-1} h^{-1}, K_m = 3.32 kPa and K_i = 17.2 kPa for the R_{CO2} of spinach; V_m = 5.717 mmol kg^{-1} h^{-1}, K_m = 5.92 kPa and K_i = 140.6 kPa for the R_{O2} of king oyster mushrooms; V_m = 2.386 mmol kg^{-1} h^{-1}, K_m = 0.03 kPa and K_i = 85.0 kPa for the R_{CO2} of king oyster mushrooms. With simple glance on the respiration parameters, king oyster mushroom is of higher respiration activity due to its higher values of V_m.

Eqs. (1)~(3) were solved numerically by using Gear's method to have partial pressures of O_2, CO_2 and N_2 (p_{O2}, p_{CO2} and p_{N2}) or to volumetric percentages under 1 atm converted from gas moles.

Results and Discussion

With adequate dimension of gas diffusion tube, the sensor-controlled container system was shown to produce a beneficial MA for spinach (Fig. 1A). The gas composition was equilibrated after 8 days for $[CO_2]$ and $[O_2]$ to stay at 10% ($[CO_2]_H$) and 8~9%, respectively. The atmosphere in the sensor-controlled produce container equipped with diffusion tube has been reported formerly to be determined by only one of lower O_2 boundary ($[O_2]_L$) or upper CO_2 limit ($[CO_2]_H$) depending on the characteristics of the commodity and the optimal MA$^{7)}$. However, under certain condition of long and narrow tube (for example, 0.5 cm diameter and 6.0 cm length), $[CO_2]$ went beyond $[CO_2]_H$ and $[O_2]$ went eventually down below $[O_2]_L$, which might induce physiological injury due to too low O_2 and/or too high CO_2 concentrations (Fig. 1B). The control system of this dimension tube failed to locate the container atmosphere in the optimal MA region, because of too much activity of respiration to modify the atmosphere compared to gas transfer across the diffusion tube. The O_2 and CO_2 gas transfers through long and narrow tube were not enough to balance the spinach respiration. Simulations using Eqs. (1)~(3) were conducted for different combinations of tube diameter and length to figure out the container atmosphere depending on the tube dimension. The matrix of tube diameter and length could be divided into two regions: one to provide the desirable MA and the other to induce the too high CO_2 accumulation (Fig. 2). The adequate tube dimension was the combinations of larger diameter and shorter length in the range of 0.3~2 cm diameter and 0.2~10 cm length. Large diameter could afford long length, but small diameter could not afford too long length in the limited extent of analysis. Under the limitation of analysis boundary, the diameter size does matter but not the length of the tube: length can be anywhere in the range of 0.2~10 cm, but the diameter needs to be appropriate size depending on the tube length. As a simple approx-

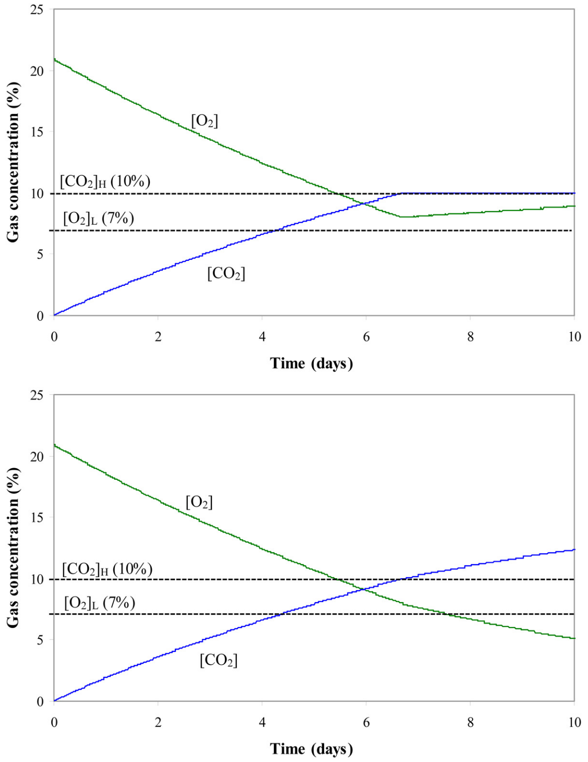


Fig. 1. Container atmosphere profiles of spinach container with tube dimension in (A) adequate range (diameter 1.0 cm/length 0.2 cm) and (B) inadequate range (diameter 0.5 cm/length 6.0 cm).

		Length (cm)							
		0.2	0.5	1	3	5	6	7	10
Diameter (cm)	0.1								
	0.2								
	0.3	▨							
	0.5	▨	▨	▨					
	0.7	▨	▨	▨					
	0.9	▨	▨	▨	▨				
	1	▨	▨	▨	▨	▨			
	1.3	▨	▨	▨	▨	▨	▨	▨	▨
	1.5	▨	▨	▨	▨	▨	▨	▨	▨
	1.7	▨	▨	▨	▨	▨	▨	▨	▨
	2	▨	▨	▨	▨	▨	▨	▨	▨

Fig. 2. Adequate range of tube dimension capable of maintaining beneficial MA close to the optimum (O_2 7~10%/CO_2 5~10%) for spinach. Shaded area represents the adequate combination of tube diameter and length, while the other white one is non-adequate combination.

length could make the desired MA condition.

Similarly to spinach container, adequate tube dimension could attain beneficial MA staying at $[O_2]$ of ≈5% and $[CO_2]$ of 15% after equilibration (Fig. 3A). As observed in spinach container (Fig. 1A), the $[CO_2]$ resided at the upper tolerable limit of CO_2 concentration ($[CO_2]_H$), which is 15% for king oyster mushroom. Before reaching the $[CO_2]$ equilibrium, $[O_2]$ stayed at the lower limit of 2% ($[O_2]_L$) for some time. The sensor-based control could create and maintain the beneficial safe MA by playing on the borderline of $[O_2]_L$ or $[CO_2]_H$. The effective control like Fig. 3A was attained with several possible combinations of tube diameter and length, which were presented in Fig. 4. With different adequate tube dimensions there were slight variations in the equilibrium $[O_2]$ attained along with $[CO_2]$ at $[CO_2]_H$.

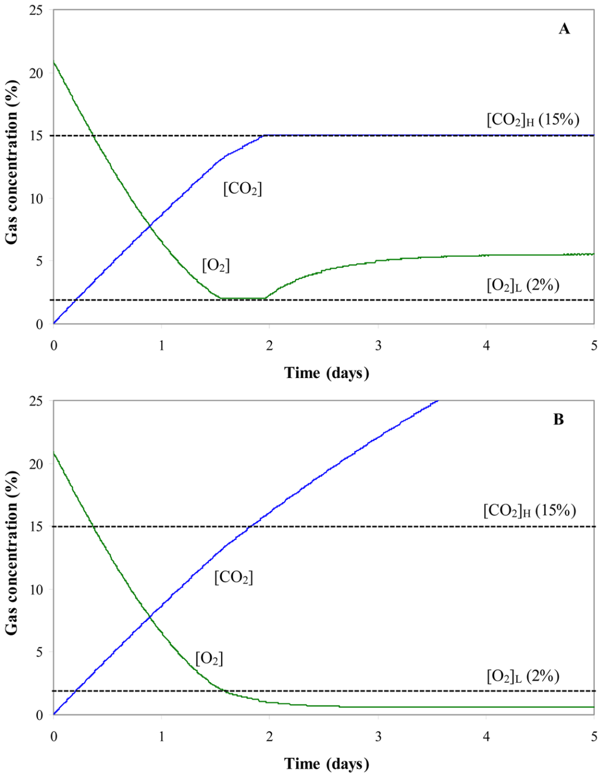
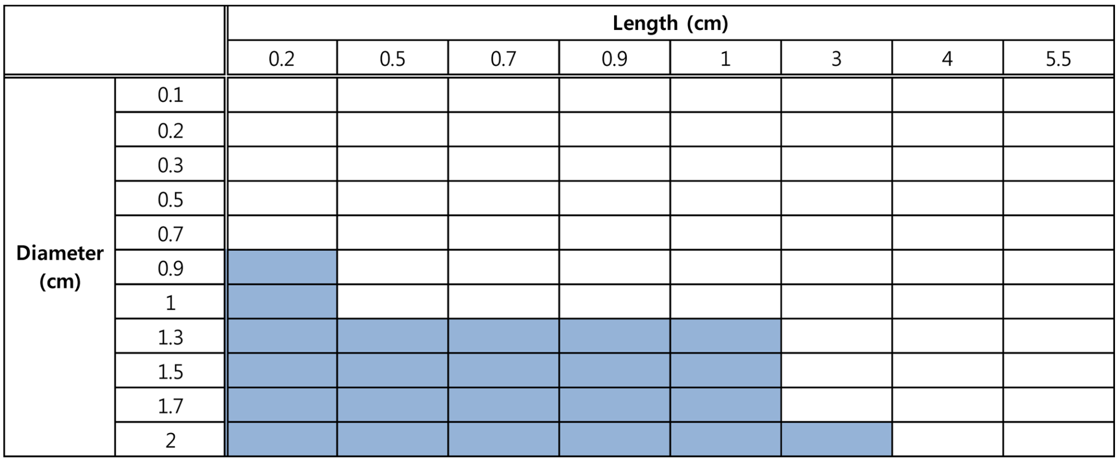


Fig. 3. Container atmosphere profiles of king oyster container with tube dimension in (A) adequate range (diameter 1.0 cm/length 0.2 cm) and (B) inadequate range (diameter 0.7 cm/length 4.0 cm).

On the other hand, tube of narrow diameter and long length resulted in persistently increased $[CO_2]$ well above $[CO_2]_H$ without reaching equilibrium along with anaerobic condition of $[O_2] < 1\%$ (Fig. 3B), which may be detrimental to the mushroom physiology. The larger gas diffusion resistance across the tube due to small perforation area and long length made the gas transfer not high enough to balance the mushroom respiration. The increased $[CO_2]$ level in the injurious range was higher with narrower diameter and longer length of the tube. Fig. 4 shows also non-tolerable range of tube dimension in terms of attainable gas composition. Adequate domain of tube dimension consisting of larger diameter and shorter length in the king oyster mushroom container was smaller in the analyzed boundary and disposed more in the direction of larger diameter and shorter length in comparison to that of spinach. As a rough and simple view, any tube dimension of 1.3~2 cm in diameter and 0.2~1 cm in length seems OK to attain a beneficial MA condition close to optimum (O_2 2~5%/CO_2 10~15%). This is because of higher respiration activity of king oyster mushroom in the container than that of spinach (high V_m values in respiration model parameters and greater fill weight (W)).

Even though the control regime of the sensor-controlled MA container system can maintain the desired MA condition inside the container, it is valid only under the adequate dimension of gas diffusion tube. Thus the domain for the adequate



		Length (cm)							
		0.2	0.5	0.7	0.9	1	3	4	5.5
Diameter (cm)	0.1								
	0.2								
	0.3								
	0.5								
	0.7								
	0.9	■							
	1	■							
	1.3	■	■	■	■	■			
	1.5	■	■	■	■	■			
	1.7	■	■	■	■	■			
	2	■	■	■	■	■	■		

Fig. 4. Adequate range of tube dimension capable of maintaining beneficial MA close to the optimum (O_2 2~5%/CO_2 10~15%) for king oyster mushroom. Shaded area represents the adequate combination of tube diameter and length, while the other white one is non-adequate combination.

dimensions needs to be figured out for any specific system of commodity, fill weight and container volume. The approach used in this study may be applied to the different systems for effective container design. General picture on affordable tube dimension depending on the commodity and pack conditions may be constructed from further study applying many different variables. It also needs to be mentioned that this kind of control is more adoptable for large size container than for small package.

Conclusions

Even though the real-time control of opening/closing of the gas diffusion tube in response to the measured O_2 and CO_2 concentrations can create and maintain the desired MA in the produce container, achievement of the desired MA condition is found to be possible only under adequate ranges of the diffusion tube dimension. Adequate dimensions need to be determined in consideration of the produce respiration characteristics and container conditions.

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