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Research Paper

An adaptively controlled modified atmosphere container system for fresh produce

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Time-variable open/close cycles of a gas diffusion tube may serve as a means to supply the desired gas transfer to attain a beneficial modified atmosphere (MA) in fresh produce containers. Because the produce respiration contributing to the atmosphere modification changes over time, adoption of real-time respiration in the open/close control of the tube may be an innovative tool to maintain the container atmosphere. An adaptive control of the tube responding to the real-time respiration of fresh produce was developed based on a simplified O_2 mass balance to generate and maintain the desired MA for the fresh produce. Here, the O_2 concentration change in the initially closed container before reaching the target value was used to calculate the respiration rate to determine the starting value of the opening ratio of the cycle time and the average O_2 concentration of each cycle after reaching the target value once was used in the mass balance relationship to update the opening ratio for the next cycle. The developed MA container system could attain the targeted O_2 concentrations and the expected desirable CO_2 concentrations for blueberries and spinach at steady state, helping to preserve their quality.

1. Introduction

Modified atmosphere (MA) packaging or containers with internal gas concentrations of reduced O_2 and elevated CO_2 in the desired range can effectively maintain fresh produce and extend the shelf life. The MA in a fresh produce package or container is created and maintained by the tailored interaction between the package's gas transfer and produce respiration (Mangaraj, Goswami, & Mahajan, 2009; Sousa-Gallagher & Mahajan, 2013). Mechanistic means to tune the gas transfer to the respiration include permeation through the plastic layer and diffusion through perforations on the package or container. Various forms of perforation, such as microperforation, gas diffusion tubes and valves, are used as additives or supplements to implement gas transfer, particularly for high-respiration produce (Rodriguez-Aguilera & Oliveira, 1998). While variables such as diameter, length and number of perforations are often used to attain the desired gas

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Nomenclature

A	area of diffusional gas flow of a tube (m^2)
B	thickness of the plastic layer (mm)
C_r	corrective index used for updating O_r (Pa)
$[CO_2]$	CO_2 concentration in the container (%)
$[CO_2]_H$	upper limit of desired CO_2 concentration range (%)
D_{O2}	O_2 diffusivity in air ($m^2\ h^{-1}$)
L_d	effective length of the gas diffusion tube corrected given as length + 1.1 diameter (m)
N	number of diffusion tubes or ratio of opening time in the case of a single diffusion tube
n_{O2}	number of O_2 moles in the container at time t
O_r	opening ratio of the cycle time
$O_{r,\ new}$	opening ratio of the cycle time for the next cycle
$O_{r,\ old}$	opening ratio of the cycle time for the current cycle
$[O_2]$	O_2 concentration in the container (%)
$[O_2]_L$	lower limit of the desired O_2 concentration range (%)
$[O_2]_r$	O_2 concentration averaged over the cycle time (%)
$[O_2]_t$	target O_2 concentration (%)
p_a	normal atmospheric pressure (1.013×10^5 Pa)
P_{O2}	partial pressure of O_2 inside the container defined as $[O_2]\ p_a/100$ at atmospheric pressure (Pa)
$\overline{p}_{O2}$	O_2 permeability of the plastic layer (mol mm $m^{-2}\ h^{-1}\ Pa^{-1}$)
R	gas constant (8.314 Pa $m^3\ K^{-1}\ mol^{-1}$)
R_{O2}	produce respiration in O_2 consumption (mol $kg^{-1}\ h^{-1}$)
S	surface area of plastic layer (m^2)
t	storage time (h)
T	temperature (K)
W	produce mass (kg)

transfer, our previous study showed that the timed opening of a gas diffusion tube could also provide the required diffusive gas flow and thus control the atmosphere of the produce container, benefitting quality preservation (Kwon, An, & Lee, 2013). The timed opening of the gas diffusion tube may be achieved by a fixed cycle time ratio or sensor activation (Jo, Kim, An, Lee, & Lee, 2013). While gas sensor-based control is instantaneously reactive and simple, it can cause wearing of the on–off opening device, limiting its direct application in practice. However, the fixed control of the tube opening based on predetermined respiration is robust but has limitations for commodities with time-variable respiration. Produce respiration changes with the surrounding atmosphere, temperature and time (Caleb, Mahajan, Opara, & Witthuhn, 2012; Fonseca, Oliveira, & Brecht, 2002). There is a requirement to measure respiration on a real-time basis to better tune the MA packaging conditions (Mahajan, Luca, & Edelenbos, 2016). The time-variable control of tube opening in response to real-time respiration measurement may have a reasonable cost and improved reliability for achieving the desired container atmosphere.

This work thus aims 1) to develop an adaptive control of the fresh produce container that achieves the desired MA considering real-time respiration and 2) to test the effectiveness of the developed MA container system in controlling the atmosphere and preserving the quality of fresh produce. A prototype container equipped with a gas diffusion tube was constructed and submitted to storage tests of blueberries and spinach.

2. Materials and methods

2.1. *Concept of the MA container system in response to real-time respiration*

A plastic container of fresh produce was conceptualised to have a gas diffusion tube and an O_2 gas sensor, as shown in Fig. 1. The diffusion tube was devised to be actuated in its cycles of open/close in response to the measured O_2 concentration interacting with fresh produce respiration. This adjustment of the open/close cycles maintains the O_2 concentration ($[O_2]$) within a desired range. In a perforation-mediated fresh produce package or container, the sum of O_2 and CO_2 concentrations remains approximately 21% (Jo, An, & Lee, 2014; Mannapperuma & Singh, 1994; Paul & Clarke, 2002), and thus, the CO_2 concentration ($[CO_2]$) may be decided by the controlled O_2 concentration, permitting the interactive manipulation and design of the desired MA. According to Jo et al. (2013), maintaining the O_2 concentration at the lower limit of its optimal range ($[O_2]_L$) or the CO_2 concentration at its upper optimal limit ($[CO_2]_H$) could place the container atmosphere at the most beneficial MA of any commodity, as long as the O_2 or CO_2 concentration does not go beyond the respective boundary limit (not below $[O_2]_L$ or not above $[CO_2]_H$). If the CO_2 concentration is expected to surpass the upper tolerable limit, the O_2 concentration may be set at a higher value than its lower limit to maintain the CO_2 concentration within the tolerable range, as shown by Jo et al. (2014). For example, spinach has an optimal MA window of 7–10% O_2 and 5–10% CO_2 (Kader, 2001) and thus should be set for the $[O_2]$ to be at

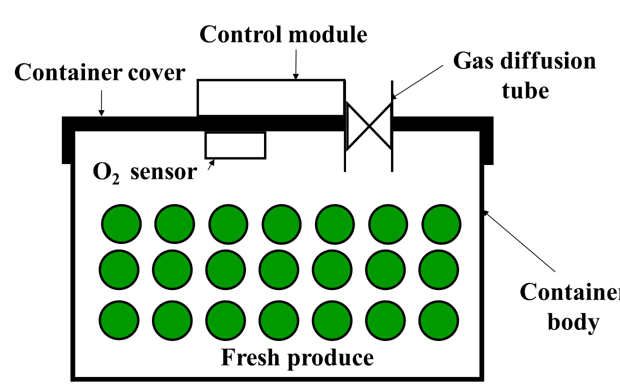

Fig. 1 – Conceptual diagram of the MA container with a gas diffusion tube controlled in the open/close cycles in a time-variable manner.