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Research Paper

Modelling water vapour transport, transpiration and weight loss in a perforated modified atmosphere packaging for feijoa fruits

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In modified atmosphere packaging (MAP), the transpiration of the fresh product and exchange of water through the polymeric packaging are often not properly considered. This paper presents a mathematical model to describe the evolution in water vapour, O_2 and CO_2 concentrations in the packaging headspace, the weight loss of the product and the condensation of water in a MAP system with perforations. Transpiration was considered as the sum of water transferred out from the product due to the gain of energy from its respiration process and the difference in water activities between the product and the surrounding atmosphere. Respiration was represented using Michaelis–Menten enzyme kinetics. The gas transfer through the packaging and the perforations was described with Fick equations. The temperature influence on these processes was considered to follow the Arrhenius' law. To experimentally determine the model parameters, feijoa fruits (*Acca sellowiana* Berg) were stored under different storage conditions: packaging type, relative humidity and temperature. The completed model was subsequently validated in a MAP test by packaging fruits in perforated polypropylene (PP) and polylactic acid (PLA) bags for 13 days at 12 °C and 75% RH. Inside the PP bags, a saturated atmosphere (100% RH) was reached and 1.48% of the initial weight in the packed fruit was lost by day 13, while in the PLA bags, an equilibrium RH of 83% and a fruit weight loss of 3.29% were measured. The prediction capacity of the model was satisfactory, with coefficients of determination (R^2) between 0.88 and 0.99 for the different tests.

1. Introduction

Modified atmosphere packaging (MAP) is a storage technology that has been widely used to extend the shelf-life of fruits, vegetables and other foods. In the case of fresh produce, it is required to reduce the rate of their metabolic processes and microbial counts by decreasing the O_2 concentration and maintaining moderate concentrations of CO_2 in the packaging headspace. This is achieved by balancing the produce

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Nomenclature

a_w	water activity
A	effective exchange area of the packaging film (m^2)
A_h	cross sectional area of the perforations (cm^2)
CWL	Cumulative weight loss in the produce
CV_{cnd}	Cumulative condensate water inside the package
d	diameter of the perforation (cm)
d_e	effective diameter of the perforations (cm)
D_i	diffusion coefficient of gas *i* in air ($cm^2\ d^{-1}$)
E_a	activation energy ($kJ\ mol^{-1}$)
k	mass transfer coefficient ($kg\ kg^{-1}\ d^{-1}$)
K_{TRi}	transmission rate of gas *i* through the perforations ($cm^3\ d^{-1}$)
L	film thickness (mm)
m_{H_2Oevp}	rate of water evaporated in the packed produce ($kg\ d^{-1}$)
P	pressure (atm)
p_i	partial pressure of gas *i* inside the package (atm)
p_{iout}	partial pressure of gas *i* outside the package (atm)
p_p	water partial pressure in the produce (atm)
P_{sat}	saturation water vapour pressure at T (atm)
q	effective respiration heat used in the water evaporation from the produce ($kJ\ kg^{-1}\ d^{-1}$)
Q_i	film permeability coefficient for gas i ($cm^3\ mm\ m^2\ d^{-1}\ atm^{-1}$)
R	universal gas constant ($0.008314\ kJ\ mol^{-1}\ K^{-1}$ or $82.057\ atm\ cm^3\ mol^{-1}\ K^{-1}$)
RH	relative humidity
r_{H_2O}	transpiration rate ($kg\ kg^{-1}\ d^{-1}$)
r_{O_2}, r_{CO_2}	O_2 consumption and CO_2 generation rates ($cm^3\ kg^{-1}\ d^{-1}$)
r_{O_2max}, r_{CO_2max}	maximum O_2 consumption and CO_2 generation rates ($cm^3\ kg^{-1}\ d^{-1}$)
t	packaging/storage time (d)
T	temperature (°C, K)
V	free package volume/packaging headspace (cm^3)
V_{cnd}	condensate water inside the package (cm^3)
W	fruit weight (kg)
Δw_{sg}	Weight change in the silica gel
y_{O_2}, y_{CO_2}, y_{H_2O}, y_{N_2}	O_2, CO_2, water vapour and N_2 concentrations inside the package
y_{O_2out}, y_{CO_2out}, y_{H_2Oout}, y_{N_2out}	O_2, CO_2, water vapour and N_2 concentrations outside the package
$y_{O_2\ eq}$, $y_{CO_2\ eq}$, $y_{H_2O\ eq}$, $y_{N_2\ eq}$	equilibrium O_2, CO_2, water vapour and N_2 concentrations inside the package
α	fraction of energy used from the respiration process to evaporate water in the fruit
ε	Correction term for gas transmission through perforations (mm)
λ	latent heat of water evaporation ($kJ\ kg^{-1}$)
ρ_{H_2O}	liquid water density ($kg\ cm^{-3}$)

respiration and the gas transfer through the packaging walls to favourable levels of O_2 and CO_2, where these levels depend on the O_2 consumption and CO_2 production rates by the produce and packaging selective permeability to these gases. A wide range of mathematical models to describe the evolution of O_2 and CO_2 in MAPs has been developed (Castellanos, Cerisuelo, Hernández-Muñoz, Herrera, & Gavara, 2016a; Del-Valle, Hernández-Muñoz, Catalá, & Gavara, 2009; Hussein, Caleb, & Opara, 2015; Kwon, Jo, An, & Lee, 2013; Mahajan, Oliveira, Montañez, & Frias, 2008; Mangaraj, Goswami, & Mahajan, 2014). These models have been used to successfully design packaging systems, allowing for the selection of the packaging material and its configuration (surface area, thickness, perforations when required in high respiring produce), which are necessary to achieve a favourable atmosphere for the packaged product. However, the effect of the transport of water from the fresh produce to the surrounding atmosphere has not been widely considered. In the MAP system, fresh produce continually loses water through transpiration. The water is lost as vapour that diffuses to the packaging headspace and then the external atmosphere being transferred through the packaging walls. If the permeability of the packaging material to water vapour is low, as with many of the most commonly used polymeric packaging materials, the packaging headspace will be saturated and part of the transpirated water will be condensed. In addition, if there are fluctuations in the storage temperature, the saturation pressure in turn will change and there will be condensation. Condensed water inside the package can lead to the growth of microorganisms and product deterioration, ruining the efforts made in the design of the modified atmosphere. On the other hand, if the permeability of the package is very high and there is a considerable difference between the water activity (a_w) of the product and the relative humidity of the external atmosphere, there will be a concentration differential that will lead to continuing loss of water from the product and, hence, undesirable weight loss.

Considering the above, an effective MAP system must consider water transport and its concentration (relative humidity) in the packaging headspace so that there is no condensation inside the package, but also so that the flow of water lost from the product to the external atmosphere is minimal.

Several models have been developed to represent the evolution in the relative humidity and water exchange in MAP systems as linked to changing levels of O_2 and CO_2 (Bovi, Caleb, Linke, Rauh, & Mahajan, 2016; Guevara-Arauza, Yahia, Cedeño, & Tijskens, 2006; Lu, Tang, & Lu, 2013; Rennie & Tavoularis, 2009; Sousa-Gallagher, Mahajan, & Mezdad, 2013; Techavises & Hikida, 2008). In these models, two major processes are considered: water generation by the packed product (transpiration) and transfer of water vapour through the package walls. As for transpiration, some authors (Lu et al., 2013; Song, Vorsa, & Yam, 2002) believe that this process is a consequence of the energy transferred to and from the product in the form of heat due to the respiration process and to the temperature difference between the fruit itself and the surroundings (headspace, packaging system and external atmosphere). Other studies (Mahajan et al., 2008; Montanaro, Dichio, Xiloyannis, & Lang, 2012; Sousa-Gallagher et al.,