Design of perforated packages to preserve fresh produce considering temperature, gas concentrations and moisture loss

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Abstract

In order to properly preserve fresh produce such as fruits and vegetables, the packaging system must have a suitable configuration to reduce its metabolic processes, microbial activity and deterioration. For this, it is necessary to establish an equilibrium modified atmosphere packaging (EMAP) with favorable concentrations of O_2 and CO_2, relative humidity (RH) and storage temperatures that do not result in chilling injury. The EMAP system is established once a balance is reached between the product's metabolism and the gas transfer through the package. For this study, a mathematical model has been developed to estimate the change in gas levels in perforated packages by considering their configuration, the respiration and transpiration in the product, the storage conditions and by using the appropriate mass and heat differential balance equations. From the developed model, a design strategy is proposed to configure the packaging system for a defined product to rapidly establish an EMAP with low O_2 and moderate CO_2 levels in the headspace to reduce the product's metabolic processes and inhibit the microbial growth. Likewise, a high enough relative humidity (80-90%) to avoid excessive water evaporation and weight loss, but minimizing the possibility of saturation inside the package to avoid moisture condensation that contributes to deterioration in the product. To validate the design strategy, two different products, banana and tomato fruits, were taken as example and packaging materials with different permeation rates to O_2, CO_2 and water vapor such as polypropylene (PP), polylactic acid (PLA) and ethylene vinyl alcohol (EVOH) were used to establish a suitable packaging configuration for each product.

Keywords: configuration, EMAP, mass balance, permeation, respiration, transpiration

INTRODUCTION

Modified atmosphere packaging (MAP) has helped to extend the shelf life of many fresh vegetable products (Bovi et al., 2016; Castellanos et al., 2016a; Xanthopoulos et al., 2012). By properly configuring the packaging, an equilibrium atmosphere can be achieved in the headspace of the system with favorable levels of O_2, CO_2 and relative humidity for the best preservation of these products (Castellanos and Herrera, 2017). The success of a MAP system lies in its becoming an effective EMAP (equilibrium modified atmosphere packaging) with appropriate gas levels (Del-Valle et al., 2009). For this, a suitable strategy for the configuration of the system should be followed (Figure 1). Initially, the characteristics of the product to be packed must be known, such as its size, maturity or ripening stage and whether it is complete or cut. The respiration and transpiration rates, favorable levels of O_2, CO_2 and RH, and the storage temperature should then be estimated, since it is necessary to determine a mass transfer needs for the packaging system from these values. That is, the O_2 flux that must be introduced and the CO_2 and water vapor fluxes that must be evacuated from the system to achieve the expected favorable levels. Based on these gas transfer needs, the packing material and the configuration of the system to be used (surface area, thickness, number and size of perforations) are evaluated. All these considerations must be made considering the cost of the

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packaging material and the size limitations that may exist.

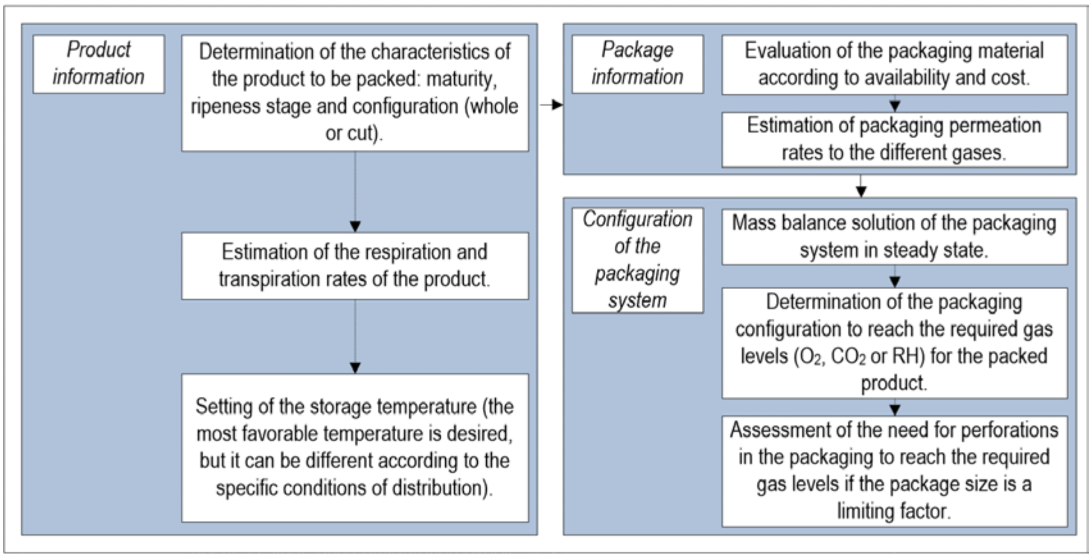

Figure 1. Strategies to configure the EMAP system.

The purpose in the configuration of the system is to achieve a balance between the mass transfer through the package and the respiration-transpiration of the packaged product in such a way that constant levels of O_2, CO_2 and RH are achieved, being these favorable for the product preservation (Castellanos and Herrera, 2017; Del-Valle et al., 2009). By analyzing the degrees of freedom of the mass balance equations for the MAP system, it is established that it is possible to configure the system to reach a specific value of one of the components in the packaging headspace, but only one. It is then preferred that this value to set is that of O_2 because it is required to keep it at low levels (2-10%) for a longer product preservation (Castellanos et al., 2016a). However, in other cases where it is desired to avoid the accumulation of condensed water it might be more convenient to set the relative humidity in the packaging headspace (Bovi et al., 2016). The numerical solution of the system of mass balance equations allows simulations of the packaging system to predefine equilibrium levels of gases to be reached before resorting to real storage experiments (Castellanos and Herrera, 2017). This numerical solution can be achieved through an appropriate calculation routine. With this it is possible to save time and resources by previously studying several possible cases according to the conservation requirements specified for a particular situation.

The aim of this study is to present a strategy for configuring an EMAP system from a mathematical model previously developed and demonstrate its usefulness in simulating the packaging of fresh produce such as tomato and banana, considering various packaging materials.

MATERIALS AND METHODS

Configuration of an EMAP system

The methodology of this study was designed to apply the configuration strategy of an EMAP system proposed in Figure 1, using a previously developed model (Castellanos et al., 2016a, b). For this, three stages were established: data collection, application of the model and simulation of results to estimate favorable gas levels.

Regarding the collection of data, two common fresh produce such as banana and tomato were selected, with abundant information about their respiration and transpiration kinetics and recommended gas levels (Castellanos et al., 2016a; Mendoza et al., 2016; Murmu and Mishra, 2016; Xanthopoulos et al., 2014). Regarding packaging materials, their permeability parameters were taken from several available studies or were estimated in previous works

(Castellanos et al., 2016a, b; Siracusa, 2012; Techavises and Hikida, 2008; Zhang et al., 2001).

The model applied to represent the MAP system was developed in previous works (Castellanos et al., 2016a, b). In this model, the respiration kinetics have been calculated from Michaelis-Menten equations. The transpiration kinetics has been calculated as the sum of the evaporated water due to the fraction of the respiration heat dissipated in the produce tissue and to the differences in water activity between the product and the packaging headspace. Mass transfer through the packaging has been calculated from diffusion Fick equations.

Finally, the parameters of respiration, transpiration and mass transfer were integrated in the model to generate simulations of the banana and tomato packaging in the EMAP system, varying the configuration in such a way that a specific O_2 concentration was reached at the recommended refrigeration temperatures for these products. From these simulations, the analysis of the evolution of the packaging system for the established configurations was made.

Mathematical modeling

For rigid packaging, the pressure will be varying with the change in the moles of gases in the system while the headspace volume can be considered constant along the storage time. In this case, the balance equations will be as follows (Castellanos and Herrera, 2017):

For O_2,

$$V\frac{dy_{O_2}}{dt} = \left(K_{TRO_2} + \frac{APQ_{O_2}}{L}\right)\left(y_{O_2out} - y_{O_2}\right) + \frac{N\pi d^4(P_{out}-P)y_{O_2}}{128\mu L_h} - r_{O_2}W - y_{O_2}\frac{V}{P}\frac{dP}{dt} \quad (1)$$

For CO_2,

$$V\frac{dy_{CO_2}}{dt} = \left(K_{TRCO_2} + \frac{APQ_{CO_2}}{L}\right)\left(y_{CO_2out} - y_{CO_2}\right) + \frac{N\pi d^4(P_{out}-P)y_{CO_2}}{128\mu L_h} + r_{CO_2}W - y_{CO_2}\frac{V}{P}\frac{dP}{dt} \quad (2)$$

For H_2O,

$$V\frac{dy_{H_2O}}{dt} = \left(K_{TRH_2O} + \frac{APQ_{H_2O}}{L}\right)\left(y_{H_2O_{out}} - y_{H_2O}\right) + \frac{N\pi d^4(P_{out}-P)y_{H_2O}}{128\mu L_h} + r_{H_2O}W - y_{H_2O}\frac{V}{P}\frac{dP}{dt} \quad (3)$$

For N_2,

$$\frac{dy_{N_2}}{dt} = 1 - \frac{dy_{O_2}}{dt} - \frac{dy_{CO_2}}{dt} - \frac{dy_{H_2O}}{dt} \quad (4)$$

where, y_i is the molar fraction (moles of gas *i* per moles of total gas in the package headspace), K_{TRi} is the transmission coefficient through the perforations and Q_i is the permeability coefficient of the packaging material for the gas *i*, where *i* corresponds to O_2, CO_2, H_2O or N_2 respectively. A is the effective area and L is the thickness of the packaging system, P is the pressure, V is the headspace volume, W is the product weight, r_{O2} is the O_2 consumption rate, r_{CO2} is the CO_2 production rate and r_{H2O} is the transpiration rate. P_{out}-P represents the difference in pressure between the packaging headspace and the external atmosphere, which results in a gas flow through the packaging system that can be described by using the Poiseuille's Law. N is the number of perforations, d is the perforation diameter, μ is the viscosity of the gas mixture (which can be considered as air) and L_h is the effective length of the perforations.

The headspace pressure change over time can be written as:

$$\frac{dP}{dt} = P\left(W\left(r_{CO_2} - r_{O_2} + r_{H_2O}\right) + \sum_{i=1}^{4}\left(\left(K_{TRi} + \frac{APQ_i}{L}\right)\left(y_{iOut} - y_i\right) + y_i\frac{N\pi d^4(P_{out}-P)}{128\mu L_h}\right)\right) \quad (5)$$

where *i* is O_2, CO_2, water vapor or N_2.

If the headspace atmosphere is saturated (RH=100%), the change in the water vapor concentration with the storage time in the headspace will be zero and the water evaporated in the product due to its transpiration will be condensing inside the package. In this case, the contribution of r_{H2O} to the pressure change in the packaging headspace is not considered in Equation 5.

The weight change in the packed product over time can be determined as follows:

$$\frac{dW}{dt} = -Wr_{H_2O}\left(\frac{PM_{H_2O}}{RT}\right) \tag{6}$$

where W is the product weight, r_{H2O} is the transpiration rate, P is the packaging pressure, R is the gas constant, T is the temperature and M_{H2O} is the water molar mass.

After presenting all the equations of the MAP system including the balance equations (Equations 1-5), numerical solutions were obtained from a calculation routine for each packaging example (Castellanos et al., 2016a). When the packaging conditions such as concentration of gases and relative humidity in the external atmosphere, atmospheric pressure, product weight, packaging material, area and thickness of the flexible or rigid package and initial gas levels, headspace volume and pressure are defined, it was possible to estimate the change in the headspace gas levels for a determined storage time. Likewise, to estimate the transfer capacity in the package to reach a suitable level of O_2 (or RH), it was necessary to estimate the transfer area of the packaging material and/or the size of the perforations required by using the mass balance equations of the MAP system in steady state. If the gas transfer capacity in the package is enough to compensate the respiration and transpiration in the packaged product, after a certain time an atmosphere of equilibrium will be reached inside the MAP system (Castellanos and Herrera, 2017).

RESULTS AND DISCUSSION

According to the conditions of preservation consulted in the literature for tomato and banana (Castellanos and Herrera, 2017; Castellanos et al., 2016a; El-ramady et al., 2015), two examples of configuration of the MAP system were established respectively. Simulations of 15 days of storage at 8°C for tomato and 13°C for banana were performed assuming 350 g of product in perforated and rigid polyethylene (PP), polylactic acid (PLA) and ethylene vinyl alcohol (EVOH) packages, modifying the material thicknesses and the number and size of the perforations in order to reach an O_2 target concentration of 5% (y_{O2}=0.05) as shown in Table 1.

Table 1. Packaging configurations to reach a specific O_2 molar fraction in the headspace (y_{O2}) for tomato and banana (moles of O_2 per moles of gas).

Target y_{O2}=0.05			
Constant packaging conditions			
Product weight		350 g	
Packaging transfer area		500 cm^2	
Headspace volume		400 cm^3	
Tomato			
Temperature		8°C	
Packaging Material	Film thickness	Perforations	y_{O2} reached
PP	0.051 mm	1×0.068 mm	0.050
PLA	0.025 mm	1×0.048 mm	0.049
EVOH	0.025 mm	1×0.037 mm	0.049
Banana			
Temperature		13°C	
Packaging Material	Film thickness	Perforations	y_{O2} reached
PP	0.020 mm	2×0.275 mm	0.050
PLA	0.020 mm	2×0.265 mm	0.049
EVOH	0.025 mm	1×0.360 mm	0.050

O_2 and CO_2 concentrations

According to the simulations performed with the three types of perforated packaging, it is possible to reach equilibrium O_2 and CO_2 concentrations in all the packaging systems by the day 15 of storage considering the particular configuration of each packaging system (Table 1).

Likewise, for the three materials, the target O_2 concentration of 5% can be reached by varying the thickness of the material or increasing the size and number of perforations.

1. Tomato.

Respecting the tomato, for the PP packages, the O_2 concentration can be reached with a film of 0.050 mm and with one perforation of 0.068 mm; for the PLA and the EVOH, with lower permeability coefficients to O_2, a film of 0.025 mm and one perforation of 0.048 and 0.037 mm would be required respectively. However, in the three perforated packaging systems, the equilibrium O_2 concentration is reached by day 12 of storage although as shown in Figure 2A, for day 5 of simulated storage, the O_2 concentration be about 7% in all three cases. This delay in the stabilization of the system is due to the low-moderate respiration rate of the tomato that required a longer time to balance with the O_2 transfer rate through the packaging walls and the perforations.

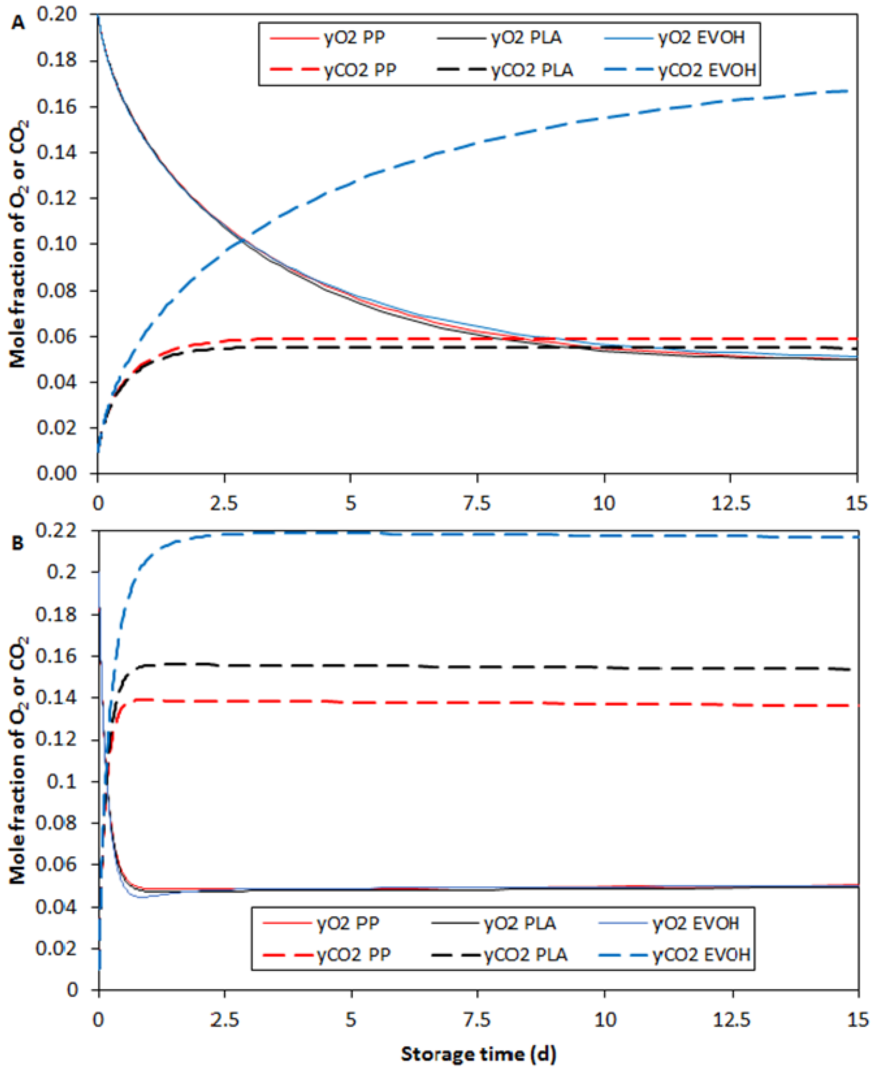

Figure 2. Predicted evolution of the O_2 and CO_2 molar fractions in perforated packages of PP, PLA and EVOH setting an equilibrium O_2 concentration of 5% (y_{O2}=0.05) for tomato (A) and banana (B).

The biggest difference between the three packaging materials is in the equilibrium CO_2 concentration reached in each case. For PP and PLA, the CO_2 molar fractions reached are similar, 0.058 and 0.054 respectively, while for EVOH the equilibrium CO_2 molar fraction would be 0.168 and it would be reached almost on day 15 of simulated storage. The low permeability of the EVOH films would lead to this high CO_2 concentration, while the higher permeability of PP and PLA would allow to reach more acceptable values and in shorter time (just over 2 days according to Figure 2A).

According to the consulted literature (Castellanos and Herrera, 2017; Majidi et al., 2014), the concentrations reached in the EMAP system for PP and PLA would be satisfactory for tomato preservation.

2. Banana.

For the simulations with banana, due to its higher respiration rate, it was necessary to increase the gas transfer capacity for the three simulated materials, decreasing the thickness of the material and increasing the size and number of perforations. In all three cases the target O_2 concentration of 5% can be reached almost perfectly in a relatively short time of about 2 days of simulated storage as shown in Figure 2B. The higher respiration rate of banana led to a shorter time to equilibrate with the gas transfer rate through the packaging and the perforation to reach the steady state.

The biggest difference again is in the CO_2 equilibrium concentrations that are high in all the simulated cases. However, the concentration reached for the EVOH is very high, approximately 21.7%. For the PLA a constant concentration of 15.4% would be reached while for the PP, due to its higher permeability, a steady concentration of 13.7% would be reached. As for O_2, equilibrium concentrations would be reached quickly for all three materials, in approximately 1 day for PP and PLA and in 2.5-3 days for EVOH. Although the CO_2 concentrations reached for the PLA and the PP are high, they can be adequate for the product preservation.

Cumulative weight loss

1. Tomato.

With the transpiration data collected from the literature for tomato (Shirazi and Cameron, 1993; Xanthopoulos et al., 2014), the accumulated weight loss for the three packing systems was simulated. The highest simulated weight loss was for the product packed in PLA, 1.2% for day 15, while the weight loss in PP and EVOH was negligible, 0.15 and 0.08% respectively (Figure 3A). In the case of PLA, an equilibrium RH of 95.4% was reached due to its higher water vapor permeability, while for PP and EVOH, the packaging headspace was quickly saturated (RH=100%). This saturation would lead to a small (<1 cm^3) condensation of moisture inside the package (according to the mass balance of the system).

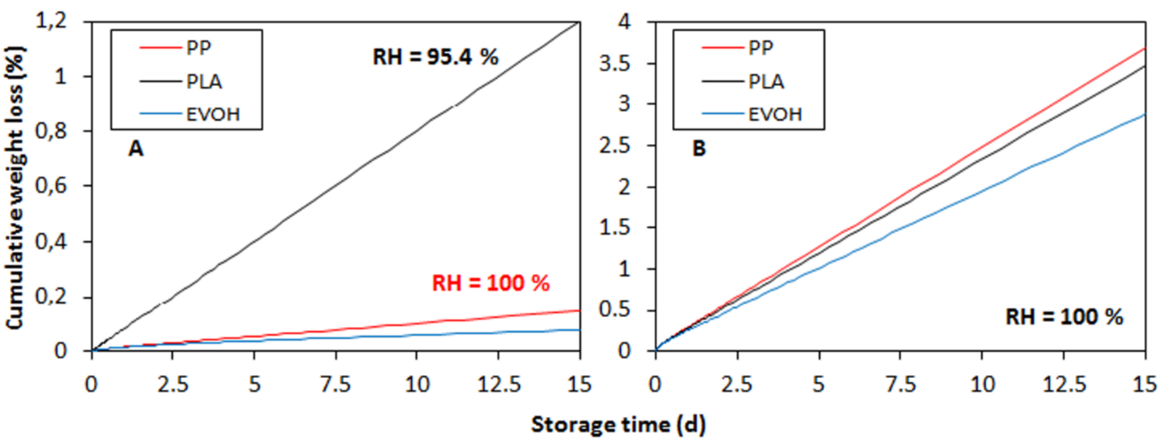

Figure 3. Predicted cumulative weight loss of tomato (A) and banana (B) in perforated packages of PP, PL A and EVOH setting an equilibrium O_2 concentration of 5% (y_{O2}=0.05). Equilibrium RH included.

Although the simulated weight loss in the tomato packaged in PLA may be greater, the equilibrium RH achieved would eliminate the risk of moisture condensation in the system.

2. Banana.

For banana, the simulation shows a cumulative weight loss of 3.7% for PP, 3.5% for PLA and 2.9% for EVOH (Figure 3B). The lower cumulative loss for EVOH is due to its lower water vapor permeability and lower transfer through the perforation. Regarding the greater weight loss of the product packaged in PP with respect to PLA (whose permeability to water vapor is higher), this is explained by the larger size of the simulated perforations for this material. The higher weight loss of banana respecting tomato, is fundamentally due to its higher transpiration rate according to the data consulted for the simulation. In all three cases, the packaging headspace was quickly saturated leading to a significant generation of condensation (8-10 cm^3 according to the simulation) which might be a possible cause of deterioration and quality loss in a real storage situation. This condensation could be avoided by increasing the transfer area of the perforations or by decreasing the thickness of the packing material, but this would also lead to an increase in the equilibrium O_2 concentration, which is the primary criterion for the configuration of the system. For this reason, the use of a moisture adsorbing material is recommended to help to balance the high transpiration rate of banana packaged in these materials.

According to the simulations performed, the packaging system with PLA would be the most satisfactory for the tomato, while PP would be the most satisfactory for the packaging of banana except that it would require an additional active element to control the moisture condensation.

CONCLUSIONS

The following conclusions can be drawn from the study:

It was possible to estimate the behavior of the O_2 and CO_2 levels and relative humidity in the perforated rigid packing system throughout the storage time for the products and packaging materials consulted.

The packaging system can be configured from the model presented in this study to establish favorable equilibrium gas concentrations for the preservation of fresh produce such as banana and tomato.

The model can represent the packaging of other types of fresh produce and the use of other types of materials by introducing the appropriate parameters of respiration, transpiration and permeability.

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