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Modeling respiration–transpiration in a modified atmosphere packaging system containing blueberry

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Abstract

A respiration–transpiration model was developed by applying simultaneous heat and mass transfer principles along with known physiological behavior for the design of MAP systems containing fresh produce. The model equations were solved numerically using Adams–Moulton method to predict gas compositions, RH, and temperature in model packages. The applicability of the model to packages containing blueberry at 15 and 25 °C was successfully verified using different types of packaging films. The difference between the experimental and predicted headspace gas composition was less than 1%. The predicted and experimental values were in agreement for RH (within 2%) and temperature (within 0.5 °C).

1. Introduction

Respiration and transpiration rates are vital factors that determine the gas compositions and relative humidity (RH) of modified atmosphere packages (MAP) containing fresh produce. Improper control of the gas compositions may lead to undesirable results such as anaerobic respiration, accelerated physiological decay, and shortened shelf life. High RH inside the package causes microbial growth and moisture condensation (Dennis, 1985; Kader, Zagory, & Kerbel, 1989), and low RH causes shriveling and moisture loss. Predicting and controlling respiration and transpiration rates in MAP systems is a complicated task that is best accomplished with the aids of computer models.

Several researchers have developed models to estimate respiration rates as a function of O_2 and/or CO_2 concentrations (Yang & Chinnan, 1988; Cameron, Boylan-Pett, & Lee, 1989; Talasila, Chau, & Brecht, 1990; Lee, Haggar, Lee, & Yam, 1991). Among these models, the enzyme kinetics type respiration model developed by Lee et al. (1991) is a simple model that appears to have some theoretical basis, and its applicability has been demonstrated for a wide variety of commodities (Haggar, Lee, & Yam, 1992; Song, Kim, & Yam, 1992).

Mathematical modeling of transpiration rates in MAP systems is not well developed for at least two reasons. First, the modeling requires good understanding of the dynamic interactions between evaporation on the produce surface by heat of respiration and permeation through the package film. Unfortunately, the transpiration phenomenon of fresh produce at changing O_2 and CO_2 environment is not well understood, and little work has been done on predicting the RH and temperature in MAP systems. Second, the applicability of existing models to predict moisture loss and temperature in fresh produce (Sastry & Buffington, 1982; Chau & Gaffney, 1985; Gaffney, Baird, & Chau, 1985) is limited to cooling process and bulk storage, and these models may not be suitable for MAP applications.

In this study, a respiration–transpiration model was developed by applying simultaneous heat and mass transfer principles along with known physiological behavior for the design of MAP systems containing fresh produce. The model predictions for gas compositions, RH and temperature were evaluated with experimental data of blueberry packaged in modified atmospheres.

2. Model development

2.1. Assumptions

The respiration–transpiration model developed here describes the simultaneous respiratory and transpiratory

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Nomenclature

$[CO_2]$	carbon dioxide concentration (%)
$[CO_2]_i$	carbon dioxide concentration inside package (%)
$[CO_2]_o$	carbon dioxide concentration outside package (%)
$[O_2]$	oxygen concentration (%)
$[O_2]_i$	oxygen concentration inside package (%)
$[O_2]_o$	oxygen concentration outside package (%)
A_p	surface area of package (m^2)
A_s	surface area of fresh produce (m^2)
A_{p1}	surface area of top of package (m^2)
A_{p2}	surface area of bottom of package (m^2)
A_{p3}	surface area of sides of package (m^2)
C_a	humid heat of air (J kg^{-1} K^{-1})
C_s	specific heat of fresh produce (3722.1 J kg^{-1} K^{-1} according to Peleg & Bagley, 1983)
D_1	length of top in package assumed as horizontal plate (m)
D_2	length of bottom in package assumed as horizontal plate (m)
D_3	length of side in package assumed as vertical plate (m)
H_i	absolute humidity (kg/kg dry air)
h_p	convective heat transfer coefficient on surface of package (J h^{-1} m^{-2} K^{-1})
h_s	convective heat transfer coefficient on surface of produce (J h^{-1} m^{-2} K^{-1})
K_{i1}	inhibition constant in O_2 consumption (% CO_2)
K_{i2}	inhibition constant in CO_2 evolution (% CO_2)
K_{m1}	Michaelis constant in O_2 consumption (% O_2)
K_{m2}	Michaelis constant in CO_2 evolution (% O_2)
L	thickness of polymeric package film (mil)
$\dot{m}_1$	rate of water vaporization from produce to headspace (kg h^{-1})
$\dot{m}_2$	rate of water permeation from headspace to surrounding (kg h^{-1})
$\dot{m}_w$	transpiration rate of fresh produce (kg h^{-1} m^{-2})
m_w	weight of water inside package (kg)
$\bar{P}_{CO_2}$	permeability to CO_2 (ml mil m^{-2} h^{-1} atm^{-1} or ml m m^{-2} h^{-1} atm^{-1})
$\bar{P}_{H_2O}$	permeability to H_2O (ml mil m^{-2} h^{-1} atm^{-1} or ml m m^{-2} h^{-1} atm^{-1})
$\bar{P}_{O_2}$	permeability to O_2 (ml mil m^{-2} h^{-1} atm^{-1} or ml m m^{-2} h^{-1} atm^{-1})
P_i	water vapor pressure inside package (atm)
P_o	water vapor pressure outside package (atm)
P_{atm}	pressure of 1 atm (1 atm or 101325 Pa)
Q_s	respiratory heat of produce (J h^{-1} kg^{-1})
Q_{ext}	convective heat on surface of produce (J h^{-1})
Q_{int}	respiratory heat (J h^{-1})
R	gas constant (8.314 J mol^{-1} K^{-1})
RH_i	relative humidity inside package (%)
RH_o	relative humidity outside package (%)
$RH_{i,i}$	initial relative humidity inside package (%)
$RH_{o,b}$	relative humidity on package boundary (%)
r	respiration rate in O_2 consumption or CO_2 evolution (ml kg^{-1} h^{-1} or mmol kg^{-1} h^{-1})
r_{CO_2}	respiration rate in CO_2 evolution (ml kg^{-1} h^{-1} or mmol kg^{-1} h^{-1})
r_{O_2}	respiration rate in O_2 consumption (ml kg^{-1} h^{-1} or mmol kg^{-1} h^{-1})
T_i	temperature inside package (°C)
T_o	temperature outside package (°C)
T_s	temperature on surface of produce (°C)
$T_{i,i}$	initial temperature inside the package (°C)
t	time (h)
V	free volume (ml)
V_{m1}	maximum O_2 consumption rate (ml kg^{-1} h^{-1})
V_{m2}	maximum CO_2 evolution rate (ml kg^{-1} h^{-1})
W_a	weight of dry air inside package (kg)
W_s	weight of produce (kg)
Greeks	
α	conversion factor (ranged from 0.8 to 1.0)
λ	latent heat of vaporization (J kg^{-1})

behavior of a rectangular modified atmosphere package containing fresh produce. The model uses the following assumptions:

1. The fresh produce, the package headspace, and the surrounding are initially at the same temperature.
2. Since the headspace is small, thermal equilibrium between the produce and the headspace is assumed to reach within a short time.
3. A large portion (between 80% and 100%) of the respiratory energy released by the produce is dissipated as heat.
4. The respiratory heat is the only internal heat source and can be expressed using the following respiration equation

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 2816\ \text{kJ} \tag{1}$$

The respiratory quotient (RQ) is defined as the ratio of the volume of CO_2 released to the volume of O_2 consumed. Eq. (1) is based on the oxidation of glucose in which RQ = 1. In reality, many other substrates such as organic acids are oxidized together with glucose in the respiration process. When these other substrates are oxidized, the values of RQ can range from 0.7 to 1.3 for aerobic respiration (Kader et al., 1989). The model here is based on the oxidation of glucose, and the variability of RQ was considered by taking average value of the oxygen consumption and carbon dioxide evolution (see Eq. (3)).

5. The respiration rates of the produce are functions of O_2 and CO_2 concentrations, and they follow the Michaelis–Menten type respiration model (Eqs. (4) and (5)). This assumption is valid only for aerobic conditions.
6. The temperature change in the headspace is small, and thus its effect on the respiration model parameters and permeability of packaging film can be ignored.

2.2. Mathematical model

The model is based on heat and mass balances accounting for the respiratory and transpiratory behavior of fresh produce, and the transport phenomenon across the package.

2.2.1. Respiration–transpiration occurring on produce surface

There are two sources of energy: (a) internal heat (Q_{int}), or heat of respiration of produce; and (b) external heat (Q_{ext}), or convective heat occurring on the produce surface.

The internal heat is expressed by

$$Q_{\text{int}} = Q_s W_s, \tag{2}$$

where Q_s is heat of respiration estimated from Eq. (1) and by assuming respiration rate is the average of O_2 consumption and CO_2 evolution rates

$$Q_s = \left(\frac{2816}{6}\right)\left(\frac{r_{O_2} + r_{CO_2}}{2}\right)\alpha. \tag{3}$$

The above equation was obtained from (Kang & Lee, 1998), except with an addition of the parameter α, which may be considered as a conversion factor of respiration energy dissipated as heat. The literature seems to suggest that α has a range between 0.8 to 1.0 (Burton, 1982; Powrie & Skura, 1991). For 100% conversion, α becomes one.

The r_{O_2} and r_{CO_2} are O_2 consumption rate and CO_2 evolution rate (ml kg^{-1} h^{-1}), respectively, and can be described by the Michaelis–Menten type respiration model (Lee et al., 1991)

$$r_{O_2} = \frac{V_{m1}[O_2]_i}{K_{m1} + \left(1 + [CO_2]_i/K_{i1}\right)[O_2]_i}, \tag{4}$$

$$r_{CO_2} = \frac{V_{m2}[O_2]_i}{K_{m2} + \left(1 + [CO_2]_i/K_{i2}\right)[O_2]_i}, \tag{5}$$

where the transient behavior of $[O_2]_i$ and $[CO_2]_i$ can be obtained using mass balance equations developed by Hayakwa, Henig, and Gilbert (1975),

$$\frac{d[O_2]_i}{dt} = (100)\frac{\frac{A_p \bar{P}_{O_2} P_{\text{atm}}}{L}\left[\frac{[O_2]_o}{100} - \frac{[O_2]_i}{100}\right] - W_s r_{O_2}}{V}, \tag{6}$$

$$\frac{d[CO_2]_i}{dt} = (100)\frac{\frac{A_p \bar{P}_{CO_2} P_{\text{atm}}}{L}\left[\frac{[CO_2]_o}{100} - \frac{[CO_2]_i}{100}\right] + W_s r_{CO_2}}{V}. \tag{7}$$

If the package headspace initially contains air, the initial conditions ($t = 0$) become

$$[O_2]_i = 21.0, \tag{8}$$

$$[CO_2]_i = 0.03. \tag{9}$$

Similarly, if the package is placed in air, $[O_2]_o = 21.0$ and $[CO_2]_o = 0.03$ for all time.

The external heat is expressed as

$$Q_{\text{ext}} = h_s A_s (T_i - T_s), \tag{10}$$

where h_s is convective heat transfer coefficient of produce surface.

A heat balance may now be written by equating the internal heat, the external heat, the latent heat of moisture vaporization, and the sensible heat for increasing the produce temperature as follows:

$$Q_s W_s + h_s A_s (T_i - T_s) = \dot{m}_i \lambda + W_s C_s \frac{dT_s}{dt}, \tag{11}$$

where $\dot{m}_1$ is rate of vaporization from fresh produce to package headspace, λ is latent heat of vaporization, and C_s is specific heat of the produce.

Apply the assumption $T_i = T_s$, and the external heat becomes negligible. Eq. (11) may then be simplified as

$$Q_s W_s = \dot{m}_1 \lambda + W_s C_s \frac{dT_s}{dt}. \tag{12}$$

The rate of vaporization $\dot{m}_1$ may be obtained from (Kang & Lee, 1998)

$$\dot{m}_1 = \frac{Q_s W_s - W_s C_s \frac{dT_s}{dt}}{\lambda}. \tag{13}$$

2.2.2. Moisture permeation through package

The rate of moisture permeated from the headspace to the surrounding through the package is expressed by

$$\frac{dm_w}{dt} = \left[\frac{\bar{P}_{H_2O} A_p (P_i - P_o)}{L}\right]\left[\frac{0.018 P_{\text{atm}}}{R T_s}\right], \tag{14}$$

where the driving force of permeation is the water vapor pressure difference between package headspace and surrounding. At a constant temperature, there are two possible situations to consider: when the headspace water vapor pressure is (1) less than or equal to, and (2) higher than the saturated vapor pressure.

In the first case, when P_i is less than or equal to the saturated vapor pressure P_{sp}, the moisture permeation rate from the headspace to the surrounding is expressed by

$$\dot{m}_2 = \left[\frac{\bar{P}_{H_2O}A_p(P_i - P_o)}{L}\right]\left[\frac{0.018P_{atm}}{RT_s}\right]. \quad (15)$$

In the second case, when P_i is higher than P_{sp}, Eq. (15) still holds. However, super saturated vapor condenses on the produce or the film surface, and the latent heat of condensation will cause the temperature of the produce and the headspace to increase.

2.2.3. Rate of RH change in headspace

The rate of moisture accumulation in headspace is expressed by

$$\frac{dH_i}{dt} = \frac{\dot{m}_1 - \dot{m}_2}{W_a}, \quad (16)$$

where H_i is absolute humidity. The initial condition is

$$RH_i = RH_{i,i} \quad \text{at } t = 0 \quad (17)$$

RH_i as a function of time can be estimated using Eq. (16) and psychrometric equations (Toledo, 1991).

2.2.4. Rate of temperature change in headspace

The overall energy balance on the package is

$$Q_sW_s + h_pA_p(T_o - T_i) = \dot{m}_2\lambda + W_sC_s\frac{dT_s}{dt} + W_aC_a\frac{dT_s}{dt}. \quad (18)$$

The initial condition is

$$T_i = T_{i,i} \quad \text{at } t = 0. \quad (19)$$

Eq. (18) can be arranged to give the rate of temperature change inside the package

$$\frac{dT_s}{dt} = \frac{Q_sW_s - \dot{m}_2\lambda - h_pA_p(T_i - T_o)}{W_sC_s + W_aC_a}, \quad (20)$$

where T_o is temperature of the surrounding. h_p is convective heat transfer coefficient of package surface, which can be estimated by assuming natural convection of air in laminar range using the equation (Toledo, 1991)

$$h_p = 3600\left[\frac{0.59A_{p1}\left(\frac{T_i-T_o}{D_1}\right)^{0.25}}{A_p} + \frac{1.32A_{p2}\left(\frac{T_i-T_o}{D_2}\right)^{0.25}}{A_p} + \frac{1.42A_{p3}\left(\frac{T_i-T_o}{D_3}\right)^{0.25}}{A_p}\right], \quad (21)$$

where D_1, D_2, and D_3 are the dimensions of top, bottom and side, respectively, of a rectangular package. The top of the package is assumed as a horizontal small plate facing upward when cooled, the bottom as a horizontal small plate facing downward when cooled, and the side as vertical small plates.

In short, the respiration–transpiration model consists of four simultaneous first order differential Eqs. (6), (7), (16), and (20). Computer programs in Fortran codes based on Adams–Moulton methods (Gerald, 1970) were developed to solve these governing equations numerically. The programs predict transient state gas compositions, RH, and temperature inside model packages containing blueberry under various conditions.

3. Materials and methods

3.1. Fresh produce

Early season 'Duke' highbush blueberries (*Vaccinium corymbosum* L.) were harvested in Hammonton, New Jersey during early summer. The maturity of the fruits was the grade 'blue,' meaning 90% of the berry surface was blue with 10% pink around the scar (Windus, Shutak, & Gough, 1976). Uniform size of samples were selected and equilibrated at 15 and 25 °C for 6 h before experiment.

3.2. Estimation of respiration model parameter values

Respiration rates of blueberries as a function of O_2 and CO_2 concentrations were measured at 15 and 25 °C using the closed system method described by Haggar et al. (1992). Each experiment involved placing about 250 g of blueberries in a 2-l glass jar that was tightly closed with a metal cap. The metal cap had a silicone sampling port through which 1 ml of headspace sample was periodically withdrawn. The headspace samples were analyzed for O_2 and CO_2 concentrations using a Hewlett Packard 5890A gas chromatograph equipped with a thermal conductivity detector and an Alltech CTR I column (Alltech Associates, Deerfield, IL). Helium was used as carrier gas, the flow rate was 65 ml/min, and the column temperature was 30 °C. The headspace analysis was terminated when the CO_2 level inside the jar was above 15% or the O_2 level was below 2%, to avoid exceeding the upper and the lower tolerance limits. The closed jars were stored in a refrigerator controlled at 15, 25 ± 0.5 °C during the experiment. Three replicates were used for each condition.

Respiration data from the above experiments were used to estimate the respiration model parameters (V_m, K_m and K_i) for the following linearized forms of Eqs. (4) and (5):

$$\frac{1}{r_{O_2}} = \frac{1}{V_{m1}} + \frac{K_{m1}}{V_{m1}}\frac{1}{[O_2]} + \frac{1}{K_{i1}V_{m1}}[CO_2], \quad (22)$$

$$\frac{1}{r_{CO_2}} = \frac{1}{V_{m2}} + \frac{K_{m2}}{V_{m2}}\frac{1}{[O_2]} + \frac{1}{K_{i2}V_{m2}}[CO_2]. \quad (23)$$

Multiple linear regression analysis for estimating the parameters was performed using the statistical software JMP (SAS Institute, 1993).

3.3. Permeable package experiments for model verifications

Permeable model packages were used to verify the respiration–transpiration model. These model packages were rectangular in shape with surface area of 0.069 m^2, similar to commercial packages. Two kinds of plastic films were used to construct packages for model verifications. Orega was a LDPE film containing 5% zeolite, and Clean-Plas was a photo-degradable LDPE film containing 10% starch, both obtained from ChoYang Film, Korea. The average thicknesses of the films were 1.78 ± 0.2 and 1.33 ± 0.2 mil (or 45.2 and 33.9 μm), respectively. The gas permeabilities of the films measured using the iso-static method (Karel, Issenberg, Ronsivalli, & Jurin, 1963) at 15 and 25 °C are presented in Table 1. Since these films were plasticized, the O_2 and CO_2 permeabilities were lower, and water vapor permeabilities were higher than those of unplasticized films (Yasuda & Stannett, 1975). The films were preconditioned at the experimental temperatures before experiment.

The applicability of the enzyme kinetics respiration model parameters to estimate the respiration rates at any O_2 and CO_2 concentration was tested by measuring gaseous compositions inside the model packages as a function of time. The experimental variables were package films (Orega and Clean-Plas films), weight of blueberry (200 and 250 g), and temperature (15 and 25 °C). The experiment involved storing the packages at 15 or 25 °C and taking 1 ml headspace samples periodically through a silicone sampling port for gas chromatographic analysis. Sampling continued until the O_2 level within the package reached 2.0%. The free volume inside the package was measured by injecting 20 ml of methane into the package and measuring the resultant dilution after a period of equilibration.

The respiration–transpiration model was verified by monitoring RH and temperature histories inside the model packages containing 200 g blueberry at 15 and 25 °C. A thermocouple and a HMP130 Y humidity sensor with accuracy of ±1% RH (Vaisala, Finland) were inserted into the model packages, and the temperature and RH were monitored over time using the data acquisition system WorkBench (SCI, NY). After storing the package for three days at the experimental temperatures, the free volume inside the package was measured using the procedure mentioned above. The relative humidities outside the packages at 15 and 25 °C were 10% and 60%, respectively.

Table 1
Permeability data for different types of film

Type of film	Gas	$\bar{P}$ 10^{-3} (ml m h^{-1} m^{-2} atm^{-1})	
		15 °C	25 °C
Orega	O_2	5.6 ± 0.3	9.2 ± 0.3
	CO_2	20.9 ± 0.7	33.0 ± 0.6
	H_2O	450 ± 16	703 ± 25
Clean-Plas	O_2	7.9 ± 0.3	11.7 ± 0.4
	CO_2	27.2 ± 1.3	36.0 ± 1.0
	H_2O	474 ± 17	725 ± 21

4. Results and discussion

4.1. Enzyme kinetics respiration model parameter values

Respiration rates of 'Duke' blueberry of different picking dates at 15 and 25 °C obtained from the closed system experiments were used to fit the respiration model of Eqs. (22) and (23). The estimated values of the parameters are presented in Table 2. The regression equation fitted the data very well with the coefficient of determination $R^2 > 0.98$. With these estimated values, respiration rates at other combinations of O_2 and CO_2 concentrations can now be predicted with Eqs. (22) and (23).

4.2. Verification of enzyme kinetics respiration model

The model parameter estimates in Table 2 were verified by comparing predicted and experimental gas compositions inside the permeable model packages containing blueberry at 15 and 25 °C. The predicted gas compositions were obtained by solving Eqs. (6) and (7), using the Adams–Moulton method.

Fig. 1(a) and (b) show fairly good agreements between the predicted and experimental headspace gas compositions for model packages constructed of Orega film. Due to the low O_2 permeability of the film and the high respiration rates of blueberry at 25 °C, the O_2 concentrations inside both model packages dropped rapidly down below 2% level, when anaerobic respiration occurred.

Fig. 2(a) and (b) also show fairly good agreements between the predicted and experimental headspace gas compositions for model packages constructed of Clean-Plas film. For the model package containing 200 g

Table 2
Parameter estimates of the respiration model, V_m, K_m and K_i for 'Duke' Blueberry at 15 and 25°C determined by multiple linear regression of Eqs. (22) and (23)

Picking Date	Temperature (°C)	V_m (mL kg^{-1} h^{-1})	K_m (% O_2)	K_i (% CO_2)	R^2
Parameters for O_2 consumption curves:					
1st (July 8)	15	22.71	7.63	14.42	0.985
2nd (July 22)	25	28.20	0.12	16.65	0.999
Parameters for CO_2 evolution curves:					
1st (July 8)	15	17.64	5.08	11.99	0.987
2nd (July 22)	25	21.09	0.09	52.41	0.999

R^2 is the coefficients of determination.

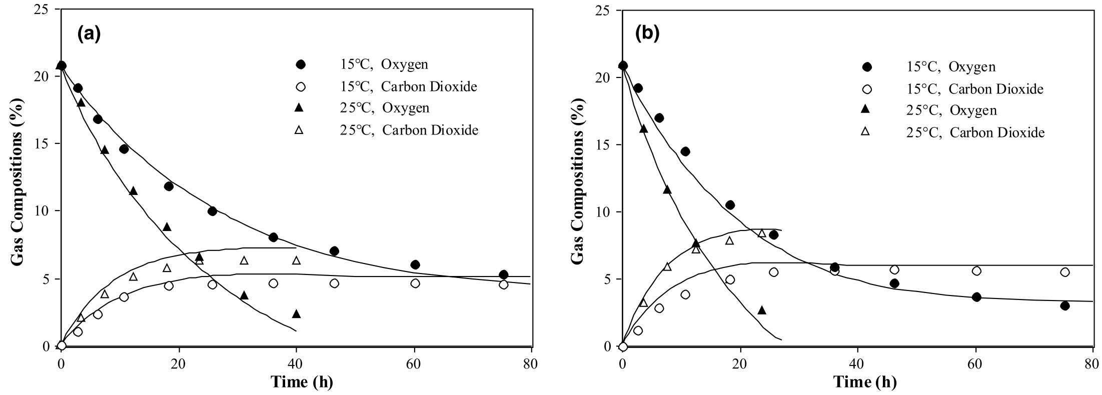

Fig. 1. Gas compositions inside model packages (using Orega film) as a function of time at 15 and 25 °C: (a) 200 g blueberry, 492 ml free volume, (b) 250 g blueberry, 426 ml free volume. The symbols are experimental values and the solid lines are predictions using Eqs. (6) and (7).

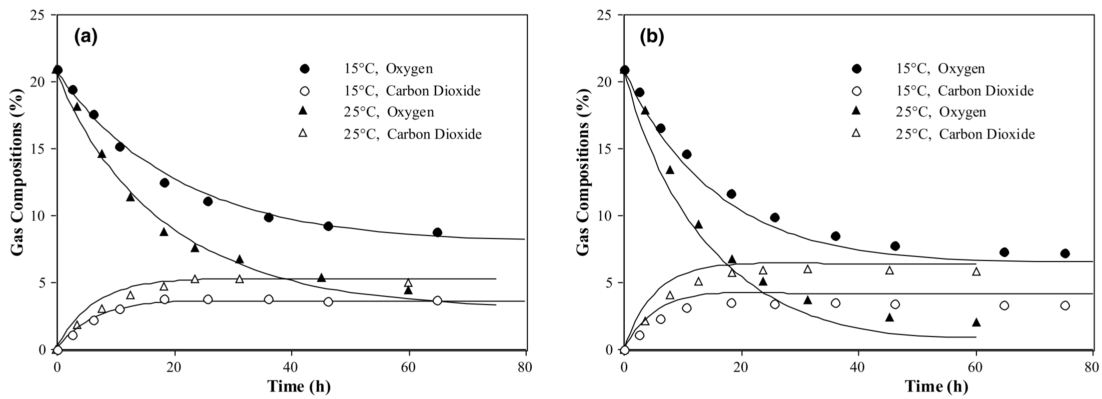

Fig. 2. Gas compositions inside model packages (using Clean-Plas film) as a function of time at 15 and 25 °C: (a) 200 g blueberry, 489 ml free volume, (b) 250 g blueberry, 413 ml free volume. The symbols are experimental values and the solid lines are predictions using Eqs. (6) and (7).

blueberry at 15 °C, the high CO_2 permeability of Clean-Plas film resulted in low accumulation of the CO_2 concentration inside the package (Fig. 2(a)). As with the previous model package simulations, the high respiration rates of the blueberry and the low O_2 permeability of the Clean-Plas film did not permit the prediction of an equilibrium condition for the package of 250 g blueberry at 25 °C (Fig. 2(b)).

The applicability of respiration model to actual blueberry packaging systems were successfully verified through the above permeable package experiments. It justifies the assumption of the respiration–transpiration model mentioned earlier that respiration rates of fresh produces are functions of concentration of O_2 and C_{O_2}, and follow the enzyme kinetics respiration model.

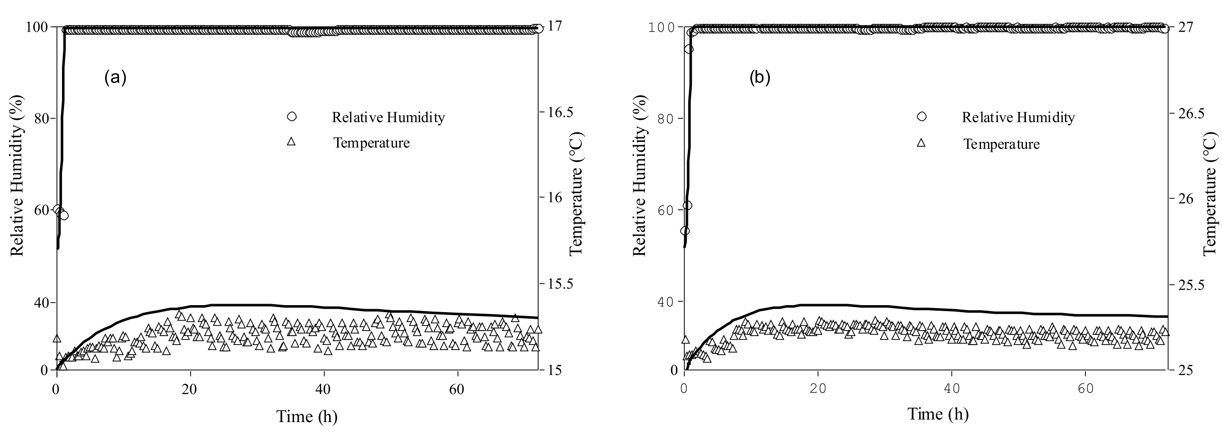

Fig. 3. Relative humidity and package environmental temperature in model packages (using Clean-Plas film) as a function of time at 15 °C: (a) 200 g blueberry, 550 ml free volume, (b) 200 g blueberry, 554 ml free volume. The symbols are experimental values and the solid lines are predictions.

4.3. Verification of respiration–transpiration model

The transient RH and temperature inside the model packages as a function of time at 15 and 25 °C were simulated by numerically solving Eqs. (6), (7), (16), and (20) using Adams–Moulton method. The conversion factor α of 0.95 was used because it provided the best fit of the data. The values in Tables 1 and 2 were used for the model verifications. Clean-Plas was used as packaging film because of its higher water vapor permeability.

Fig. 3(a) and (b) show good agreements (within 2%) between the predicted and experimental relative humidity as a function of time inside the model packages at 15 and 25 °C. Both packages were saturated (100% RH) rapidly during storage. This situation was a result of the small headspace inside the packages and the relatively low water vapor transmission of the film compared to water vapor transpiration of blueberry.

Computer simulations were performed using other permeability values of commercially available films. The results suggested that controlling RH below 100% was unlikely by varying film permeability alone. Therefore, the use of other means such as moisture absorber is necessary to control RH.

Fig. 3(a) and (b) also show good agreements (within 0.5 °C) between the predicted and experimental relative humidity and package environmental temperature as a function of time inside the model packages at 15 and 25 °C. Both the model predictions and experimental data show that the temperature increases slightly at the beginning. The increase in temperature justifies our assumption that the saturated vapor condenses on the film and produce surface, and the latent heat of condensation causes the temperature of the produce and the headspace to increase.

5. Conclusions

The applicability of the enzyme kinetics respiration model was verified using permeable packages containing blueberries at 15 and 25 °C. The model parameters were obtained and incorporated into the respiration–transpiration model. The good agreements between the predicted and experimental RH and temperature support the validity of the respiration–transpiration model. The results showed that RH could not be controlled below 100% with existing commercial films.

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