KOREAN JOURNAL OF PACKAGING SCIENCE & TECHNOLOGY
Vol. 21, No. 1 1~10 (2015)

Compilation of Respiration Model Parameters for Designing Modified Atmosphere Package of Fresh Produce

Duck Soon An and Dong Sun Lee*

Department of Food Science and Biotechnology, Kyungnam University, Changwon 631-701 Korea

Abstract Enzyme kinetics-based respiration model can be effectively used for estimating respiration rate in O_2 consumption and CO_2 production of fresh produce as a function of O_2 and CO_2 concentrations. Arrhenius equation can be applied to describe the temperature dependence of the respiration rate. Parameters of enzyme kinetics-based respiration model and activation energy of Arrhenius equation were compiled from analysis of literature data and closed system experiment. They enable to estimate the respiration rate for any modified atmosphere conditions at temperature of interest and thus can be used for design of modified atmosphere packaging of fresh produce.

Keywords Enzyme kinetics based respiration model, Arrhenius equation, Oxygen consumption, Carbon dioxide production, Modified atmosphere, Temperature

Introduction

Modified atmosphere packaging (MAP) of low oxygen and high carbon dioxide is an effective tool for keeping fresh produce and extending its shelf life. Each produce has its own optimal modified atmosphere (MA) conditions with O_2 and CO_2 tolerance limits$^{1)}$. Thus the desired MA conditions may be presented as a window of O_2 and CO_2 concentrations inside the produce package. Because the atmosphere modification is determined by interaction between produce respiration and gas permeation of package, MAP design consists of balancing these two factors by controlling the variables such as produce mass, film material and thickness, and package dimension$^{2,3)}$. Respiration and gas permeation rates change with temperature being different each other in their temperature dependence. Thus package design at certain temperature cannot be applied to other temperatures and thus different temperature condition requires additional new set of package condition for maintaining the optimal MA.

As a way to design the MAP system for fresh produce systematically and conveniently, the respiration data and the package gas permeability data are combined through mathematical modelling$^{2-4)}$. Some mathematical respiration models have been proposed and their model parameters have been reported for some commodities to estimate respiration rate at specific MA of O_2 and CO_2 concentrations$^{5,6)}$. Data base on the gas permeability has also been compiled for easy and optimal selection of the packaging material$^{7,8)}$. More elaborated forms of package design tool are developed as the user-friendly software incorporating all the information on produce respiration and package gas permeability$^{9,10)}$.

In all the developments of systematic design of fresh produce package, accumulation of respiration data is essential for its convenient and versatile application to a variety of commodities and situations. We found that respiration rate data are scattered or provided without well-organized form. In order to have respiration data in easily applicable form, effect of gas composition and temperature needs to be summarized in mathematical relationship and presented in an easy-to-use data base.

Appreciating the need for comprehensive respiration database, we collected respiration data and formulated them into the parameters of the mathematical model.

Materials and Methods

Currently respiration model based on enzyme kinetics (Eq. (1)) is most widely accepted and used to describe the functional dependence of respiration on MA:

$$R_{O2} \text{ or } R_{CO2} = \frac{V_m[O_2]}{K_m + (1 + [CO_2]/K_i)[O_2]} \tag{1}$$

where R_{O2} and R_{CO2} are O_2 consumption rate and CO_2 production rate (mmol kg^{-1} h^{-1}), respectively, $[O_2]$ is O_2 concen-

---

†Corresponding Author : Dong Sun Lee
Department of Food Science and Biotechnology, Kyungnam University, Changwon 631-701 Korea
Tel : +82-55-249-2687, Fax : +82-505-999-2171
E-mail : dongsun@kyungnam.ac.kr

tration or partial pressure (atm), $[CO_2]$ is CO_2 concentration or partial pressure (atm), and V_m, K_m and K_i are parameters of maximum respiration (mmol kg^{-1} h^{-1}), Michaelis-Menten constant (atm) and inhibition constant (atm), respectively[11].

Literatures which report the parameters of respiration model for any specific commodities, preparation conditions and temperatures, were collected. The reported parameters were converted in units given above. In some cases the model parameters were calculated from the respiration data given in the literatures. For some commodities where effect of CO_2 concentration on respiration has been reported to be negligible, an arbitrary value of 10 was given to negate any effect of CO_2 on respiration in model calculation. For chestnut, king oyster mushroom, shiitake mushroom, peach and strawberry, the model parameters at 3 different temperatures were determined from experimental data by using the closed system method[12,13]. Fully ripe chestnut was purchased as Yipyung variety from a farm in Chungju, Korea in October 2010. King oyster mushroom, Saesongyi #1 was from a market in Changewon, Korea in April 2011. Shiitake mushroom, Deokgang #2 was from a farm in Miryang, Korea in August 2014. Ripe peach in variety of Manseng-Hwangdo was from Gimcheon, Korea in August 2010. Strawberry as Sulhyang variety was purchased from a market in Changwon, Korea in December 2012. All the purchased or delivered products were immediately submitted to the closed system experiment after precooling or temperature adjustment.

Temperature dependence of respiration rate is commonly expressed by Arrhenius Equation:

$$R_i = R_{i,o}\exp\left(\frac{-E_a}{RT}\right) \tag{2}$$

where R_i is R_{O2} or R_{CO2}, $R_{i,o}$ is preexponential factor for R_{O2} or R_{CO2}, respectively, E_a is the activation energy (J mol^{-1}), R is the gas constant (8.314 J K^{-1} mol^{-1}) and T is the absolute temperature (K)[2,8,14,15].

Activation energy in Eq. (2) enables to predict the produce respiration rate at temperature of interest from that given at a temperature. Activation energy is usually not dependent significantly on MA, and one single value may be used to describe temperature dependence of respiration for various MA conditions[12,16-19]. Thus activation energy value was determined by the regression analysis of respiration data which were obtained for an MA of 10% O_2 (0.1 atm) and 10% CO_2 (0.1 atm). Our analysis on the reported respiration data has also shown that the activation energy generally lies in a limited narrow range regardless of atmospheric composition. Atmospheric condition of 10% O_2 and 10% CO_2 was applied as typical MA just for convenience. In some rare cases where the activation energy was reported directly in the source, that value was complied straight into data base of this study.

Some literatures have reported that temperature dependence of the parameters (V_m, K_m and K_i) in Eq. (1) can be described simply by Arrhenius equation to estimate the respiration rate for any MA at any temperature[15,20-22]. However, other literatures could not find any simplified relationship on temperature dependence of the parameters[12,17] and consensus has not been reached yet on functional expression on the temperature effect. Currently practically sound way of estimating or determining respiration at new temperature from that at another temperature seems to be applying Arrhenius equation to respiration rate itself in a limited temperature range, which was adopted in this study.

Results and Discussion

The model parameters extensively collected or determined from the literature data were presented in Table 1. The parameters obtained from the experiments for chestnut, king oyster mushroom, shiitake mushroom, peach and strawberry were also given in Table 1. The parameters, V_m, K_m and K_i make it possible to estimate the respiration rate for any gas composition consisting of O_2 and CO_2 concentrations at certain temperature. They can be easily used to predict the package gas composition for different combinations of package variables such as produce weight and package film, which is very useful for the design of the fresh produce package. Various design methods of fresh produce MAP have been developed or proposed combining produce respiration and package gas permeation[3,4,23].

Fig. 1 shows an example of respiration rate calculated from the parameter values of carambola in Table 1. The respiration rates of O_2 consumption (R_{O2}) at 15°C were calculated and plotted three-dimensionally for different combinations of O_2 and CO_2 concentrations by substituting 0.398 mmol kg^{-1} h^{-1}, 0.164 atm and 0.102 atm for V_m, K_m and K_i, respectively. For example, R_{O2} for normal atmosphere (0.21 atm of O_2 and 0 atm of CO_2) could be obtained as 0.223 mmol kg^{-1} h^{-1}, that for an MA of 0.10 atm O_2 and 0.10 atm CO_2 as 0.110 mmol kg^{-1} h^{-1}, and that for an MA of 0.05 atm O_2 and 0.10 atm CO_2 as 0.076 mmol kg^{-1} h^{-1}. When magnitudes of V_m, maximum respiration rate were compared among different commodities around 15°C as a measure of respiration intensity, a large variability was observed. For example, Annurea apple slice has very low V_m of 0.348 mmol kg^{-1} h^{-1} in O_2 consumption at 15°C, while that of broccoli floret is very high being 10.666 mmol kg^{-1} h^{-1} at same temperature. Higher V_m for cut broccoli (16.207 mmol kg^{-1} h^{-1} at 13°C) is due to preparation stress on the produce. K_m indicating sensitivity to oxygen and K_i indicating sensitivity to carbon dioxide also have wide variability. It seems risky to guess the respiration model parameters without experimental measurement. Therefore respiration kinetics of any fresh produce and preparation state needs to be measured or figured out directly for designing MAP.

Table 1. Respiration model parameters for fresh produce

Commodity & variety	Temp. (°C)	O_2 consumption				CO_2 production				Reference
		V_m (mmol kg^{-1} h^{-1})	K_m (atm)	K_i (atm)	E_a (J K^{-1} mol^{-1})	V_m (mmol kg^{-1} h^{-1})	K_m (atm)	K_i (atm)	E_a (J K^{-1} mol^{-1})	
Apple, Red Delicious	0	0.544	0.036	0.141	14200	1.010	0.092	0.158	10360	Mahajan & Goswami[20)]
	5	0.616	0.049	0.111		1.074	0.096	0.141		
	10	0.701	0.066	0.100		1.168	0.105	0.128		
	15	0.914	0.075	0.085		1.447	0.119	0.113		
	20	1.123	0.085	0.081		1.645	0.129	0.094		
	25	1.320	0.089	0.055		1.817	0.132	0.101		
	30	1.768	0.089	0.061		2.269	0.141	0.078		
Apple, Cox's	3.3	0.246	0.042	0.031						Peppelenbos & van't Leven[6)]
Apple, Golden Delicious	19	1.039	0.070	0.338						Peppelenbos & van't Leven[6)]
Apple, Elstar	19.6	0.670	0.049	0.427						Peppelenbos & van't Leven[6)]
Apple-4 slices/ fruit, Annurca	5	0.162	0.004	10.000	47700	0.178	0.004	10.000	47700	Torrieri et al.[24)]
	10	0.239	0.006	10.000		0.263	0.006	10.000		
	12.5	0.289	0.007	10.000		0.318	0.007	10.000		
	15	0.348	0.008	10.000		0.383	0.008	10.000		
	20	0.500	0.012	10.000		0.550	0.012	10.000		
Apple-slices (1.5 cm wide), NY 674	0	0.220	0.007	10.000	68020	0.220	0.007	10.000	68020	Lakakul et al.[25)]
	5	0.467	0.009	10.000		0.467	0.009	10.000		
	10	0.817	0.011	10.000		0.817	0.011	10.000		
	15	1.311	0.014	10.000		1.311	0.014	10.000		
Asparagus	18.6	2.105	0.032	0.372						Peppelenbos & van't Leven[6)]
Banana	19	0.590	0.036	10.000						Makino et al.[26)]
Bellflower root	5	1.101	0.315	0.015	70140	1.103	0.151	0.021	63130	Kwon & Lee[27)]
Bell peppers-shredded, 0.4×1 cm	7	1.460	0.008	10.000	72700					Jacxsens et al.[15)]
Blueberry, Blueray	5	0.517	0.016	0.117	63520	0.392	0.007	0.196	72150	Song et al.[17)]
	15	1.466	0.001	0.068		1.277	-0.001	0.094		
	25	3.117	0.001	0.110		3.109	0.001	0.191		
Blueberry, Coville	5	0.727	0.015	0.074	61230	0.549	0.004	0.155	66610	Song et al.[17)]
	15	2.876	0.004	0.029		2.159	0.002	0.049		
	25	5.206	0.052	0.067		4.048	0.005	0.135		
Blueberry, Jersey	5	0.432	0.021	0.076	60540	0.322	0.008	0.127	67440	Song et al.[17)]
	15	1.517	0.007	0.033		1.266	0.008	0.044		
	25	2.096	0.004	0.094		1.972	0.001	0.167		
Blueberry, Duke	15	0.961	0.076	0.144	61763	0.746	0.051	0.120	68733	Song et al.[28)]
	25	1.153	0.001	0.167		0.862	0.001	0.524		
Blueberry, Elliot	15	1.161	0.070	0.128	39100	1.259	0.094	0.085	54930	Song et al.[29)]
	25	1.837	0.059	0.148		1.965	0.025	0.099		
Blueberry, Blue Crop	0	0.121	0.004	0.170	42960	0.131	0.000	0.967	45900	Lee et al.[30)]
	5	0.171	0.012	1.178		0.173	0.011	-0.219		
	10	0.320	0.037	-0.116		0.462	0.022	-1.748		
	15	0.950	0.029	0.035		1.425	0.028	0.032		
	20	1.521	0.010	0.025		1.524	-0.007	0.040		
	25	2.364	0.037	0.032		1.817	0.017	0.143		

Table 1. Respiration model parameters for fresh produce (Continued)

Commodity & variety	Temp. (°C)	O_2 consumption				CO_2 production				Reference
		V_m (mmol kg^{-1} h^{-1})	K_m (atm)	K_i (atm)	E_a (J K^{-1} mol^{-1})	V_m (mmol kg^{-1} h^{-1})	K_m (atm)	K_i (atm)	E_a (J K^{-1} mol^{-1})	
Broccoli	18.7	7.057	0.061	0.080						Peppelenbos & van't Leven[6)]
Broccoli, Naomidori	16	6.470	0.018	10.000						Makino et al.[26)]
Broccoli-cut 6.5 cm, Premium Crop	0	2.642	0.022	0.051	62700	2.067	0.015	0.072	66100	Haggar et al.[12)]
	7	9.149	0.006	0.023		10.232	0.017	0.019		
	13	16.207	0.014	0.022		20.222	0.015	0.016		
	24	27.747	0.032	0.040		31.675	0.001	0.029		
Broccoli-floret	2	1.438	0.165	$5.14x10^5$	98300					Jacxsens et al.[15)]
	4	1.373	0.144	$4.24x10^6$						
	7	2.330	0.106	$1.12x10^7$						
	10	3.595	0.137	$1.32x10^6$						
	12	4.450	0.125	$1.12x10^7$						
	15	10.666	0.187	$2.41x10^6$						
Carambola, Jue-Du	10	0.271	0.173	0.127	46420	0.250	0.173	0.127	46420	Duan et al.[31)]
	15	0.398	0.164	0.102		0.367	0.164	0.102		
	20	0.549	0.157	0.089		0.507	0.157	0.089		
	25	0.756	0.135	0.081		0.699	0.135	0.081		
	30	1.037	0.128	0.072		0.961	0.128	0.072		
Carrot-cut, 5 cm	10	1.193	0.012	0.033		0.653	0.008	0.083		Lee et al.[32)]
Carrot-grated, 0.3x0.3x4 cm	7	3.415	0.057	10.000	85900					Jacxsens et al.[15)]
Carrot-shredded	12	0.906	0.004	0.407	69000	1.087	0.004	0.407	69000	Iqbal et al.[16)]
Cauliflower	1					0.173	0.003	10.000	94630	Rati et al.[33)]
	6.5					0.405	0.004	10.000		
	12					0.920	0.007	10.000		
	23					4.331	0.018	10.000		
Cauliflower-cut, 5 cm	13	4.181	0.017	0.030		3.054	0.014	0.031		Yam et al.[34)]
Cherry, Burlat (O_2 2-10%)	2	0.133	0.060	10.000	83300					Jaime et al.[35)]
	5	0.438	0.110	10.000						
	20	1.954	0.060	10.000						
Cherry, Burlat (O_2 10-21%)	2	0.354	0.290	10.000	83300					Jaime et al.[35)]
	5	1.884	0.710	10.000						
	20	4.282	0.290	10.000						
Cherry, Sunburst (O_2 2-10%)	2	0.089	0.030	10.000	83300					Jaime et al.[35)]
	5	0.088	0.010	10.000						
	20	0.707	0.050	10.000						
Cherry, Sunburst (O_2 10-21%)	2	0.177	0.160	10.000	83300					Jaime et al.[35)]
	5	0.219	0.170	10.000						
	20	2.162	0.320	10.000						
Cherry, Sweet-heart (O_2 2-10%)	2	0.089	0.070	10.000	83300					Jaime et al.[35)]
	20	0.540	0.020	10.000						
Cherry, Sweet-heart (O_2 10-21%)	2	0.266	0.460	10.000	83300					Jaime et al.[35)]
	20	2.037	0.300	10.000						

Table 1. Respiration model parameters for fresh produce (Continued)

Commodity & variety	Temp. (°C)	O_2 consumption				CO_2 production				Reference
		V_m (mmol kg^{-1} h^{-1})	K_m (atm)	K_i (atm)	E_a (J K^{-1} mol^{-1})	V_m (mmol kg^{-1} h^{-1})	K_m (atm)	K_i (atm)	E_a (J K^{-1} mol^{-1})	
Chestnut-Yipyung	0	0.234	0.005	1.479	48640	0.094	0.000	1.474	63010	This study
	10	0.835	0.054	0.371		0.276	0.000	0.969		
	20	1.983	0.094	0.393		0.663	0.003	0.931		
Chicory-cut, 4 cm^2	8.1	2.557	0.052	0.081						Peppelenbos & van't Leven[6)]
Chicory endive-head	7	0.716	0.071	10.000	106000					Jacxsens et al.[15)]
Coleslaw mix, Shredded cabbage & carrot (80:20)	5	0.995	0.011	0.232	74800	0.995	0.011	0.232	84200	McLaughlin & O'Beirne[14)]
Cucumber-cut, 5 cm	10	1.289	0.044	0.013		0.858	0.035	0.007		Lee et al.[32)]
Cucumber-cut, 0.3 cm	7	0.228	0.037	10.000	79300					Jacxsens et al.[15)]
Curled lettuce	3	0.354	0.008	0.034		0.190	0.028	0.442		An et al.[36)]
French beans-cut, 0.1 cm	7	1.504	0.092	10.000	145000					Jacxsens et al.[15)]
Garlic-cut, 2 mm thick	10	1.511	0.023	0.060		1.065	0.011	0.099		Lee et al.[32)]
Garlic-peeled	5	1.054	0.032	0.137	79730	0.442	0.005	0.360	129780	Lee & Lee[13)]
	10	1.607	0.025	0.370		1.136	0.015	0.757		
Ginseng	5	0.959	0.186	0.065	57750	1.050	0.048	0.054	62920	Kwon & Lee[27)]
Green pepper	10	1.048	0.053	0.037		0.548	0.010	0.027		Lee et al.[32)]
Green pepper	10	1.698	0.056	0.013		0.722	0.024	0.043		Lee et al.[37)]
Green pepper-cut, 0.5 cm thick	5	0.859	0.022	0.102	70450	0.406	0.005	0.278	80730	Lee et al.[32)]
	10	1.197	0.024	0.253		0.801	0.009	0.200		
Kale-shredded, 1.5 mm	1	0.886	0.003	0.150	71990	0.824	0.003	0.150	71990	Fonseca et al.[38)]
	5	1.434	0.006	0.184		1.333	0.006	0.184		
	10	2.618	0.012	0.236		2.435	0.012	0.236		
	15	4.782	0.024	0.303		4.447	0.024	0.303		
	20	8.737	0.049	0.389		8.126	0.049	0.389		
Lettuce-cut, 2 cm, *Lactuca sativa* L.	5	0.332	0.009	0.385	85000	0.259	0.009	0.385	85000	Geysen et al.[39)]
Lettuce-iceburg, cut, 1 cm	7	0.230	0.057	10.000	79300					Jacxsens et al.[15)]
Lettuce-iceburg, cut, 2×1.55 cm	5	0.515	0.003	10.000	53060	0.324	0.003	10.000	72070	Smyth et al.[40)]
	10	0.767	0.002	10.000		0.558	0.002	10.000		
Lettuce-shredded, 9 cm^2 square	15	1.170	0.025	10.000						Makino et al.[26)]
Mungbean sprouts	17.9	1.189	0.008	0.131						Peppelenbos & van't Leven[6)]
Mungbean sprouts	7	0.196	0.005	10.000	126000					Jacxsens et al.[15)]
Mushroom, *Agaricus bisporus*	4	0.893	0.001	10.000	77380	0.703	-0.003	10.000	80720	Cliffe-Byrnes & O'Beirne[18)]
	8	1.352	-0.001	10.000		1.105	-0.006	10.000		
	10	2.018	0.010	10.000		1.535	-0.002	10.000		
	13	2.975	0.017	10.000		2.428	0.008	10.000		
	16	3.820	0.009	10.000		3.125	0.003	10.000		

Table 1. Respiration model parameters for fresh produce (Continued)

Commodity & variety	Temp. (°C)	O_2 consumption				CO_2 production				Reference
		V_m (mmol kg^{-1} h^{-1})	K_m (atm)	K_i (atm)	E_a (J K^{-1} mol^{-1})	V_m (mmol kg^{-1} h^{-1})	K_m (atm)	K_i (atm)	E_a (J K^{-1} mol^{-1})	
Mushroom, *Agrocybe chaxingu* Huang	3	2.946	0.032	0.150		3.110	0.026	0.154		Li & Zhang41)
Mushroom, *Agaricus bisporus*	12	2.720	0.041	0.386	54380	2.337	0.032	0.579	56040	Iqbal et al.42)
Mushroom- king oyster	0	3.128	0.106	0.793	52570	0.901	0.002	0.887	61900	This study
	10	5.717	0.058	1.388		2.386	0.000	0.839		
	20	8.254	0.013	1.728		5.510	0.000	1.325		
Mushroom-shitake	10	4.563	0.001	0.145	80430	3.479	0.000	0.175	70820	This study
	20	14.914	0.028	0.150		9.707	0.000	0.136		
Mushroom-sliced, 6 mm	4	0.966	-0.002	10.000	77450	0.790	-0.005	10.000	77710	Cliffe-Byrnes & O'Beirne18)
	8	1.532	0.001	10.000		1.258	-0.004	10.000		
	10	2.239	0.011	10.000		1.735	0.001	10.000		
	13	3.176	0.015	10.000		2.628	0.010	10.000		
	16	4.337	0.009	10.000		3.729	0.011	10.000		
Onion-cut, 0.5 cm	5	0.608	0.052	0.121	60970	0.254	0.000	0.386	51640	Lee et al.32)
	10	1.181	0.140	0.087		0.414	0.001	0.208		
Onion-cut, 0.5 cm	10	0.420	0.002	0.449		0.382	0.000	0.896		Lee & Renault43)
Peach-Manseng-Hwangdo	0	0.137	0.024	0.124	80660	0.058	0.003	1.036	85490	This study
	10	0.279	0.002	0.975		0.235	0.000	1.468		
	20	0.838	0.000	0.922		0.736	0.000	0.956		
Pear-cut 5-10 mm (*Pyrus communis* L. 'Rocha')	0	0.050	0.001	10.000	124940	0.065	0.001	10.000	124940	Gomes et al.21)
	5	0.139	0.002	10.000		0.181	0.002	10.000		
	10	0.388	0.008	10.000		0.505	0.008	10.000		
	15	1.082	0.026	10.000		1.407	0.026	10.000		
Perilla leaf	5	2.669	0.030	0.016	62260	2.138	0.033	0.038	63540	Kwon & Lee27)
Persimmon, Fuyu	0	0.043	0.000	2.906	85200	0.032	0.000	8.755	89100	Ahn & Lee44)
	5	0.130	0.000	2.450		0.111	0.000	5.198		
	20	1.361	0.107	0.596		1.057	0.033	0.446		
Sapota, *Achrus sapota*	0	0.544	0.036	0.141	14200	1.010	0.092	0.156	10330	Dash et al.45)
	5	0.616	0.049	0.111		1.074	0.096	0.141		
	10	0.701	0.066	0.100		1.168	0.105	0.128		
	15	0.914	0.075	0.085		1.447	0.118	0.113		
	20	1.123	0.085	0.081		1.645	0.129	0.094		
	25	1.320	0.089	0.055		1.812	0.132	0.101		
	30	1.768	0.089	0.061		2.269	0.141	0.078		
Shepherd's purse	5	9.055	0.020	0.021	46170	5.697	0.017	0.078	52590	Kwon & Lee27)
Soybean sprouts	5	3.065	0.080	0.028	90600	0.623	0.000	0.358	72060	Lee and Lee13)
	10	3.329	0.020	0.090		1.321	0.000	0.128		
Spinach	10					0.909	0.160	0.043		Mizukami et al.46)
Strawberry	3	0.445	0.010	0.087		0.278	0.018	0.080		An et al.36)
Strawberry, Sulhyang	0	0.173	0.010	0.957	85450	0.115	0.000	1.124	80280	This study
	5	0.386	0.035	1.197		0.198	0.000	1.456		
	10	0.753	0.027	0.776		0.391	0.000	1.123		

Table 1. Respiration model parameters for fresh produce (Continued)

Commodity & variety	Temp. (°C)	O_2 consumption				CO_2 production				Reference
		V_m (mmol kg^{-1} h^{-1})	K_m (atm)	K_i (atm)	E_a (J K^{-1} mol^{-1})	V_m (mmol kg^{-1} h^{-1})	K_m (atm)	K_i (atm)	E_a (J K^{-1} mol^{-1})	
Tomato, Jet Star	23	2.185	0.279	-0.147		1.486	0.015	0.160		Lee et al.[30)]
Tomato, Florida cv. Sunny	21	0.928	0.241	0.155						Peppelenbos & van't Leven[6)]
Tomato, Momotaro	16	0.390	0.028	10.000						Makino et al.[26)]
Wakegi onion-cut, 1 cm	5	2.087	0.005	0.360	23260	1.102	0.002	0.284	73460	Lee & Lee[13)]
	10	2.491	0.027	0.534		2.105	0.005	0.181		
Welsh onion-cut, 1 cm	5	2.862	0.320	0.681	39400	1.134	0.022	0.176	84280	Lee & Lee[13)]
	10	2.667	0.046	0.551		1.868	0.012	0.401		
Wild garlic	5	4.311	0.025	0.034	57430	2.971	0.012	0.138	53680	Kwon & Lee[27)]

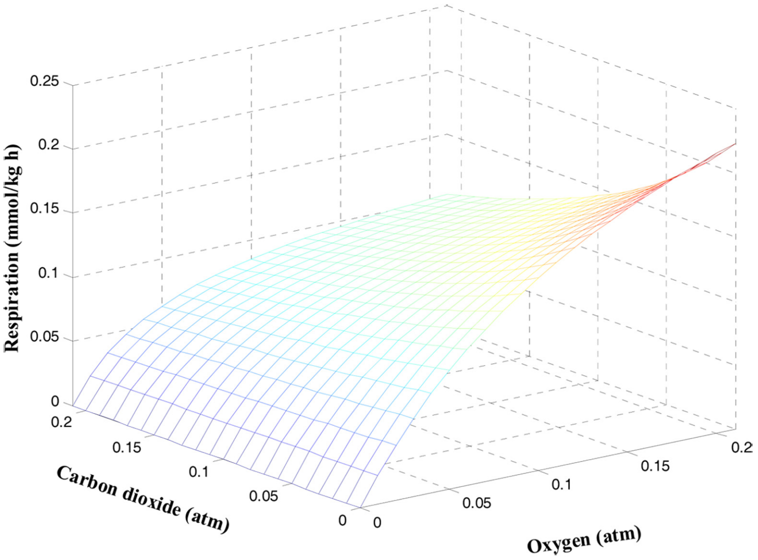

Fig. 1. O_2 consumption rate of carambola as function of O_2 and CO_2 concentrations at 15°C estimated from the parameters in Table 1.

In Table 1, activation energy values of respiration for many commodities are also provided, which enables to estimate respiration rate using Arrhenius equation relationship. For some commodities where respiration characteristics was reported only at single temperature, activation energy could not be obtained. If respiration rate is provided by Eq. (1) with parameters known for any MA condition at any temperature, the rate for the MA at any other temperature in vicinity can be calculated by Eq. (2) with using the activation energy. Thus by combining Eqs. (1) and (2) for commodities with the model parameters, the respiration rate can be calculated for MA condition at any temperatures around temperature ranges given in Table 1. Fig. 2 shows an example of Arrhenius plot for respiration rate data under an MA condition at different temperatures. The activation energy is highly variable ranging from 10.3 kJ/mol of sapota's CO_2 production to 129.8 kJ/mol of peeled garlic's. Because large variability of activation means that temperature dependence of produce respiration differ widely with commodity, response of produce MAP to temperature abuse can be very different with commodity. Considering that design of fresh produce MAP is based on the balance between respiration and package gas permeation at an optimal storage temperature, the effect of temperature fluctuation is great with produce having high activation energy. Usually activation energy of polymer's gas permeation is in the range of 22-44 kJ/mol, which is much narrower than that of produce respiration[2,8,15)]. Therefore in most commodities, temperature abuse of fresh produce MAP designed at a stor-

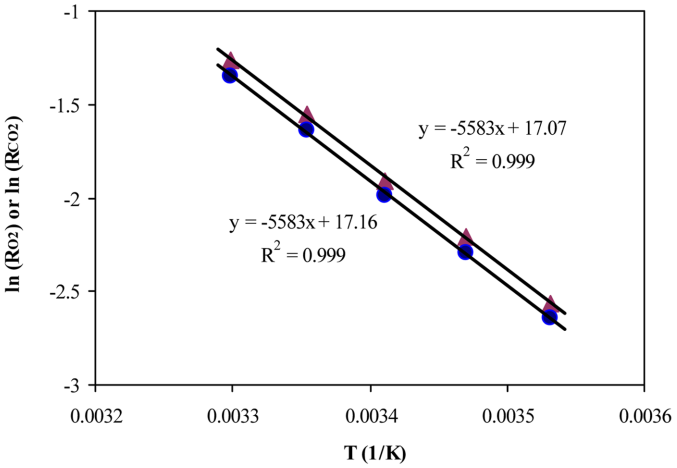

Fig. 2. Arrhenius plot of carambola respiration rate estimated at modified atmosphere of 10% O_2 (0.1 atm) and 10% CO_2 (0.1 atm) concentrations by the parameters in Table 1. ▲: O_2 consumption (R_{O2}); ●: CO_2 production (R_{CO2}).

age temperature has a high risk of lowering O_2 concentration and elevating CO_2 concentration outside optimal window. Some commodities having respiration activation energy similar to that of plastic film's gas permeation may be tolerated in temperature fluctuation.

Even though the parameters of Eqs. (1) and (2) compiled in Table 1 can estimate respiration at any desired MA and temperature conditions and thus be useful for designing optimal MAP, it needs to be noted that there exists large variability of respiration characteristics due to variety, maturity, preharvest and postharvest conditions, preparation method, etc. Thus the estimated respiration rate needs to be examined cautiously and checked with actual test, but the estimation may be able to work as a useful tool in the preliminary MAP design.

Conclusions

This study reports compilation of respiration model parameters which can estimate the respiration rate for any MA conditions at any temperatures. Enzyme kinetics based respiration model was used for describing it as function of temperature, while Arrhenius equation was employed for the MA dependence. The estimation of the respiration rate as function of O_2 and CO_2 concentrations at different temperatures can be very useful for designing optimal MAP which can preserve the produce quality well.

Acknowledgements

This study was supported by the R&D Convergence Centre Support Program of the Ministry of Agriculture, Food and Rural Affairs, Korea (Project #710003). The authors appreciate Hwan Ki Kim, Mijin Jeong and Jie Hye Lee for measuring respiration of chestnut, king oyster mushroom, peach, strawberry and shitake mushroom.

References

1. Sandhya. 2010. Modified atmosphere packaging of fresh produce: current status and future needs. LWT-Food Sci. Technol. 43: 381-392.
2. Yam, K.L. and Lee, D.S. 1995. Design of modified atmosphere packaging for fresh produce. In: Active Food Packaging. Rooney, M.L. (ed). Blackie Academic and Professional, London, pp. 55-73.
3. Hayakawa, K.I., Henig, Y.S., and Gilbert, S.G. 1975. Formulae for predicting gas exchange of fresh produce in polymeric film package. J. Food Sci. 40: 186-191.
4. Talasila, P.C. and Cameron, A.C. 1997. Prediction equations for gases in flexible modified atmosphere packages of respiring produce are different than those for rigid packages. J. Food Sci. 62: 926-930.
5. Fonseca, S.C., Oliveira, F.A.R., and Brecht, J.K. 2002. Modelling respiration rate of fresh fruits and vegetables for modified atmosphere packages: a review. J. Food Eng. 52: 99-119.
6. Peppelenbos, H.W. and van't Leven, J. 1996. Evaluation of four types of inhibition for modelling the influence of carbon dioxide on oxygen consumption of fruits and vegetables. Postharvest Biol. Tec. 7: 27-40.
7. Lee, L., Arul, J., Lencki, R., and Castaigne, F. 1996. A review on modified atmosphere packaging and preservation of fresh fruits and vegetables: physiological basis and practical aspects-part II. Packag. Technol. Sci. 9: 1-17.
8. Exama, A., Arul, J., Lencki, R.W., Lee, L.Z., and Toupin, C. 1993. Suitability of plastic films for modified atmosphere packaging of fruits and vegetables. J. Food Sci. 58: 1365-1370.
9. Mahajan, P.V., Oliveira, F.A.R., Montanez, J.C., and Frias, J.

2007. Development of user-friendly software for design of modified atmosphere packaging for fresh and fresh-cut produce. Innov. Food Sci. Emerg. 8: 84-92.

10. Lee, D.S., Jo, Y.H., Kwon, M.-J., and An, D.S. 2014. Strategy and software application of fresh produce package design to attain optimal modified atmosphere. Math. Probl. Eng. 2014: Article ID 363691.
11. Lee, D.S., Haggar, P.E., Lee, J., and Yam, K.L. 1991. Model for fresh produce respiration in modified atmospheres based on principles of enzyme kinetics. J. Food Sci. 56: 1580-1585.
12. Haggar, P.E., Lee, D.S., and Yam, K.L. 1992. Application of an enzyme kinetics based respiration model to closed system experiments for fresh produce. J. Food Proc. Eng. 15: 143-157.
13. Lee, J.J. and Lee, D.S. 1995. A dynamic test for kinetic model of fresh produce respiration in modified atmosphere and its application to packaging of prepared vegetables. Foods and Biotechnol. 5: 343-348.
14. McLaughlin, C.P. and O'Beirne, D. 1999. Respiration rate of a dry coleslaw mix as affected by storage temperature and respiratory gas concentrations. J. Food Sci. 64: 116-119.
15. Jacxsens, L., Devlieghere, F., De Rudder, T., and Debevere, J. 2000. Designing equilibrium modified atmosphere packages for fresh-cut vegetables subjected to changes in temperature. LWT-Food Sci. Technol. 33: 178-187.
16. Iqbal, T., Rodrigues, F.A.S., Mahajan, P.V., and Kerry, J.P. 2009. Mathematical modeling of the influence of temperature and gas composition on the respiration rate of shredded carrots. J. Food Eng. 91: 325-332.
17. Song, Y., Kim, H.K., and Yam, K.L. 1992. Respiration rate of blueberry in modified atmosphere at various temperatures. J. Am. Soc. Horti. Sci. 117: 925-929.
18. Cliffe-Byrnes, V. and O'Beirne, D. 2007. Effects of gas atmosphere and temperature on the respiration rates of whole and sliced mushrooms (*Agaricus bisporus*)-implications for film permeability in modified atmosphere packages. J. Food Sci. 72: E197-E204.
19. Talasila, P.C., Chau, K.V., and Brecht, J.K. 1992. Effect of gas concentrations and temperature on O_2 consumption of strawberries. Trans. ASAE. 35: 221-223.
20. Mahajan, P.V. and Goswami, T.K. 2001. Enzyme kinetics based modelling of respiration rate for apple. J. Agr. Eng. Res. 79: 399-406.
21. Gomes, M.H., Beaudry, R.M., Almeida, D.P.F., and Malcata, F.X. 2010. Modelling respiration of packaged fresh-cut 'Rocha' pear as affected by oxygen concentration and temperature. J. Food Eng. 96: 74-79.
22. Andrich, G., Zinnai, A., Balzini, S., Silvestri, S., and Fiorentini, R. 1998. Aerobic respiration rate of golden delicious apples as a function of temperature and P_{O2}. Postharvest Biol. Tec. 14: 1-9.
23. Mannapperuma, J.D. and Singh, R.P. 1994. Modeling of gas exchange in polymeric packages of fresh fruits and vegetables. In: Minimal Processing of Foods and Process Optimization. Singh, R.P. and Oliveira F.A.R. (eds). CRC Press, Boca Raton, FL, pp. 437-458.
24. Torrieri, E., Cavella, S., and Masi, P. 2009. Modelling the respiration rate of fresh-cut Annurca apples to develop modified atmosphere packaging. Int. J. Food Sci. Technol. 44: 890-899.
25. Lakakul, R., Beaudry, R.M., and Hernandez, R.J. 1999. Modeling respiration of apple slices in modified-atmosphere packages. J. Food Sci. 64: 105-110.
26. Makino, Y., Iwasaki, K., and Hirata, T. 1996. Oxygen consumption model for fresh produce on the basis of adsorption theory. Trans. ASAE. 39: 1067-1073.
27. Kwon, H.R. and Lee, D.S. 1994. Respiration characteristics of five Korean fresh vegetables. Foods Biotechnol. 3: 209-211.
28. Song, Y., Vorsa, N., and Yam, K.L. 2002. Modeling respiration-transpiration in a modified atmosphere packaging system containing blueberry. J. Food Eng. 53: 103-109.
29. Song, Y., Lee, D.S., and Yam, K.L. 2001. Predicting relative humidity in modified atmosphere packaging system containing blueberry and moisture absorbent. J. Food Process. Preserv. 25: 49-70.
30. Lee, D.S., Song, Y.S. and Yam, K.L. 1995. Application of an enzyme kinetics based respiration model to permeable system experiment of fresh produce. J. Food Eng. 27: 297-310.
31. Duan, H.-W., Wang, Z.-W., and Hu, C.-Y. 2009. Development of a simple model based on chemical kinetics parameters for predicting respiration rate of carambola fruit. Int. J. Food Sci. Technol. 44: 2153-2160.
32. Lee, K.S., Park, I.S., and Lee, D.S. 1996. Modified atmosphere packaging of a mixed prepared vegetable salad dish. Int. J. Food Sci. Technol. 31: 7-13.
33. Ratti, C., Raghavan, G.S.V., and Gariepy, Y. 1996. Respiration rate model and modified atmosphere packaging of fresh cauliflower. J. Food Eng. 28: 297-306.
34. Yam, K.L., Haggar, P.E., and Lee, D.S. 1993. Modeling respiration of low CO_2 tolerance produce using a closed system method. Foods Biotechnol. 2: 22-25.
35. Jaime, P., Salvador, R., and Oria, R. 2001. Respiration rate of sweet cherries: 'Burlat', 'Sunburst' and 'Sweetheart' Cultivars. J. Food Sci. 66: 43-47.
36. An, D.S., Park, E., and Lee, D.S. 2009. Effect of hypobaric packaging on respiration and quality of strawberry and curled lettuce. Postharvest Biol. Tec. 52: 78-83.
37. Lee, K.S., Woo, K.L., and Lee, D.S. 1994. Modified atmosphere packaging for green chili peppers. Packag. Technol. Sci. 7: 51-58.
38. Fonseca, S.C., Oliveira, F.A.R., and Brecht, J.K. 2002. Modelling respiration rate of shredded Galega kale for development of modified atmosphere packaging. J. Food Eng. 54: 299-307.
39. Geysen, S., Escalona, V.H., Verlinden, B.E., and Nicolä, B. M. 2007. Modelling the effect of super-atmospheric oxygen and carbon dioxide concentrations on the respiration of fresh-

cut butterhead lettuce. J. Sci. Food Agri. 87: 218-226.

40. Smyth, A.B., Song, J., and Cameron, A.C. 1998. Modified atmosphere packaged cut iceberg lettuce: effect of temperature and O_2 partial pressure on respiration and quality. J. Agr. Food Chem. 46: 4556-4562.
41. Li, T. and Zhang, M. 2008. Effects of modified atmosphere packaging with various sizes of silicon gum film window on the storage of *Agrocybe chaxingu* Huang and the modelling of its respiration rate. Packag. Technol. Sci. 21: 13-23.
42. Iqbal, T., Rodrigues, F.A.S., Mahajan, P.V., and Kerry, J.P. 2009. Mathematical modeling of of O_2 consumption and CO_2 production rates of whole mushrooms accounting for the effect of temperature and gas composition. Int. J. Food Sci. Technol. 44: 1408-1414.
43. Lee, D.S. and Renault, P. 1998. Using pinholes as tools to attain optimum modified atmospheres in packages of fresh produce. Packag. Technol. Sci. 11: 119-130.
44. Ahn, G.H. and Lee, D.S. 2004. Enzyme kinetics based modeling of respiration rate for ‘Fuyu’ persimmon fruits. Korean J. Food Sci. Technol. 36: 580-585.
45. Dash, K.K., Ravindra, M.R., and Goswami, T.K. 2009. Modeling of respiration of respiration rate of sapota fruit under aerobic conditions. J. Food Proc. Eng. 32: 528-543.
46. Mizukami, Y., Saito, T., and Shiga, T. 2002. Effect of controlled atmosphere on respiratory characteristics and quality preservation of spinach. Nippon Shokuhin Kagaku Kogaku Kaishi 49: 794-800.