Predicting Steady-state Oxygen Concentrations in Modified-atmosphere Packages of Tomatoes

Sannai Gong and Kenneth A. Corey
Department of Plant and Soil Sciences, University of Massachusetts, Amherst, MA 01003

Abstract. Mathematical procedures for predicting steady-state O\textsubscript{2} concentrations for a range of packaging conditions for modified-atmosphere packages (MAP) of ‘Heinz 1370’ tomato (Lycopersicon esculentum) were developed and tested. The relationship between O\textsubscript{2} consumption rate and O\textsubscript{2} concentration was determined using O\textsubscript{2} depletion data collected by enclosing tomatoes in jars and sampling head space O\textsubscript{2} concentration over time. The fitted function was then used in conjunction with the input variables film permeability to O\textsubscript{2} (P\textsubscript{02}), film surface area (A), and fruit weight in packages (W\textsubscript{p}) to develop an equation to predict steady-state O\textsubscript{2} concentrations for different packaging ratios (A/W\textsubscript{p}) and film permeabilities. Prediction curves showing steady-state O\textsubscript{2} concentration for packaging ratios in the range of 1 to 12 closely resembled best-fit curves of experimental data. Increasing temperature from 20 to 28\degree C had little effect on in-package O\textsubscript{2} concentration, but decreasing temperature from 28 to 10\degree C led to higher in-package O\textsubscript{2} concentrations. The predictive equation developed can be used to select appropriate films and optimize packaging ratios to achieve desired steady-state O\textsubscript{2} concentrations for MAP of tomatoes.

Delaying tomato fruit ripening is desirable during distribution and for short-term storage before marketing. Commercially, tomatoes intended for distant markets are usually harvested at mature-green or breaker stages so that fruit can endure the rigors of handling while maximizing shelf life. Fruit harvested at mature-green or breaker stages will ripen to the firm-red stage in 7 to 10 days and 2 to 3 days, respectively, when kept in air at 20\degree C (Hobson, 1987; Ryall and Lipton, 1979; Stenvers and Bruinsma, 1975). These times are often not sufficient for transport of fruit from production sites to distant retail markets. The incidence of over-ripe fruit often leads to increased mechanical damage in transit and has been reported as a serious problem associated with long-distance shipments taking more than a week (Geeson et al., 1985). Refrigeration and controlled atmosphere (CA) storage are effective tools for delaying ripening for long durations in transit, but are limited due to high costs and fruit sensitivity to chilling injury at temperatures below 12.5\degree C (Cheng and Shewfelt, 1988; Hobson, 1987; Ryall and Lipton, 1979).

Alternatively, an inexpensive way to delay fruit ripening is the use of modified atmosphere packaging (MAP), where fruit are sealed in semipermeable plastic packages that enable the development of a beneficial gas atmosphere created and maintained by the interaction of fruit respiration and gas diffusion through the packaging film.

An appropriate MAP for unripe tomatoes delays changes in color, acidity, soluble solids concentration, and firmness (Nakhasi et al., 1991; Yang and Chinnan, 1987). In addition, fruit kept in MAP also benefit from reduced weight loss due to maintenance of high relative humidity (Anderson and Poapst, 1983). Maximum benefits for tomatoes in MAP were obtained when the O\textsubscript{2} concentration inside the package was maintained in the range of 3\% to 5\% (Hobson, 1987; Ryall and Lipton, 1979; Stenvers and Bruinsma, 1975). These times are often not sufficient for transport of fruit from production sites to distant retail markets. The incidence of over-ripe fruit often leads to increased mechanical damage in transit and has been reported as a serious problem associated with long-distance shipments taking more than a week (Geeson et al., 1985). Refrigeration and controlled atmosphere (CA) storage are effective tools for delaying ripening for long durations in transit, but are limited due to high costs and fruit sensitivity to chilling injury at temperatures below 12.5\degree C (Cheng and Shewfelt, 1988; Hobson, 1987; Ryall and Lipton, 1979).

For this study, PO\textsubscript{2}\textsubscript{0} is the film permeability to O\textsubscript{2} (ml•cm\textsuperscript{–2}•h\textsuperscript{–1} per atm), A is the film surface area (cm\textsuperscript{2}), 0.208 is the ambient partial pressure of O\textsubscript{2} (atm), assuming the package was kept in air, and [O\textsubscript{2}]\textsubscript{p} is the partial pressure of O\textsubscript{2} in the package (atm).

Oxygen consumption by a commodity in a MAP (C\textsubscript{O\textsubscript{2}}) is calculated by multiplying the O\textsubscript{2} consumption rate at in-package O\textsubscript{2} concentrations (RR\textsubscript{O\textsubscript{2}}, ml•kg\textsuperscript{–1}•h\textsuperscript{–1} and commodity weight (W\textsubscript{p}, kilograms).

\[
C_{O_2} = RR_{O_2} W_p \tag{2}
\]

For a MAP system at steady state, the following equation can be established from Eqs. [1] and [2]:

\[
P_{O_2} A(0.208 - [O_2]_p) = RR_{O_2} W_p \tag{3}
\]

For this study, P\textsubscript{O\textsubscript{2}} for two, polyethylene + ethyl-vinyl acetate...
additive (PEVA) films (MaxPak Industries, Somerville, Mass.), with respective thicknesses of 0.033 and 0.041 mm, were determined to be 0.0620 and 0.0426 ml·cm⁻²·h⁻¹ per atm at 20°C using a steady-state technique (Gong, 1992). Oxygen consumption rates were derived from O₂ depletion data. The best-fitting function was found to be a second-order polynomial, expressed as

\[ [O_2] = at^2 + bt + c \]  \[ \text{(4)} \]

where \([O_2]\) is the O₂ concentration in the sealed jars (percent), \(t\) is the time from sealing the jar (h), and \(a\), \(b\), and \(c\) are constants.

Equation \[(4)\] was then used to derive the input variable RR \(_{O_2}\) by the following three steps. The first derivative of Eq. \[(4)\] represents the O₂ consumption rate at any time.

Second, the respiration rate of fruit at any time was calculated as

\[ \frac{d[O_2]}{dt} = 2at + b \]  \[ \text{(5)} \]

by incorporating into Eq. \[(5)\] the fruit weight, \(W_r\) (kilograms), used in the respiration measurements, and void volume, \(V\) (liter), which was calculated by subtracting the volume taken by fruit from the total volume of the respiration jar. A factor of 10 is needed for the resulting unit to be ml·kg⁻¹·h⁻¹.

Finally, a solution for \(t\) is obtained from Eq. \[(4)\] and then substituted into Eq. \[(6)\] to yield the input variable RR \(_{O_2}\):

\[ RR_{O_2} = 10(2at + b)W_r^{-1}V \]  \[ \text{(6)} \]

The predictive equation was developed by substituting Eq. \[(7)\] into Eq. \[(3)\] to give

\[ P_{O_2}A(0.208 - [O_2]_p) = (10\sqrt{b^2 - 4a(c-[O_2])}) W_r^{-1}V/W_p \]  \[ \text{(8)} \]

A second-order polynomial fit to the respiratory depletion of O₂ data yielded an \(r^2\) of 0.999 (Fig. 1). The fitted coefficients \((a = 7.07 \times 10^{-4}, b = -0.75, c = 20.64)\) were inserted into Eq. \[(7)\] along with \([O_2]_p\) values from 0% to 20% to generate a functional relationship of RR \(_{O_2}\) to \([O_2]\) (Fig. 1, inset). Oxygen consumption rate decreased sharply below \([O_2]_p\) of 6%; the RR \(_{O_2}\) at 3% being about one-third of the value at ambient \([O_2]\).

Steady-state O₂ concentrations in packages of various packaging designs were determined. An example of typical patterns for changes in O₂ and CO₂ concentrations in tomato packages are shown in Fig. 2. Oxygen concentration decreased rapidly within a day to a minimum of 4%, then gradually increased to a steady-state concentration of 6%. Carbon dioxide followed a reverse pattern, with a resulting steady-state concentration of 4%.

Packaging designs, for which steady-state O₂ concentrations were measured, included two films, several film surface areas (A), and various weights of tomatoes packaged (\(W_p\)). The packaging ratio, \(A/W_p\), varied from 1 to 12 cm²·g⁻¹ for one film (Fig. 3A) and 1 to 5 cm²·g⁻¹ for the other (Fig. 3B). Steady-state O₂ concentrations achieved in the different packages were plotted with their
Fig. 1. Nonsteady-state respiratory depletion of O₂ by tomatoes at 20°C. Points are means of three replications ± 1 sd. Inset shows derived O₂ consumption rates for various O₂ concentrations. The curve was generated from Eq. [7] shown in the text.

Fig. 2. Typical pattern of changes in O₂ and CO₂ concentrations in tomato packages at 20°C (A/Wp = 1.35 ± 0.02 cm²·g⁻¹, P₀ = 0.0426 ml·cm⁻²·h⁻¹ per atm). Points are means of four replications ± 1 sd.

Fig. 3. Comparisons of predicted steady-state O₂ concentration (solid line) with those achieved experimentally (o) in tomato packages using two films: A) 0.033-mm-thick PEVA film, P₀ = 0.062 ml·cm⁻²·h⁻¹ per atm, and B) 1.6 ml PEVA film, P₀ = 0.0426 ml·cm⁻²·h⁻¹ per atm. The dashed curve is the best nonlinear fit of data using the equation [O₂] = a[1 – e⁻b(A/Wp)], r² ≥ 0.90. Insets are plots of predicted steady-state oxygen concentrations ([O₂]P) vs. those achieved experimentally ([O₂]E). Correlation coefficients were highly significant (P < 0.01), as denoted by **. Note that the x and y axes of A and B differ in scale.

Fig. 4. Temperature fluctuations resulted in changes in steady-state O₂ concentration (Fig. 4). When fruit were initially packaged and kept at 20°C, the in-package O₂ concentration decreased rapidly to a minimum of ≈4% within a day and then gradually increased to a steady-state level of ≈6%. When packages were transferred from 20 to 28°C, the O₂ concentration increased gradually (=3 days) to a new steady state of = 7.3%. In-package O₂ concentration increased rapidly when packages were transferred from 28 to 10°C, reaching a steady-state concentration of 10.5% within 3 days.

Generalized sets of steady-state [O₂] prediction curves were developed for various packaging ratios (Fig. 5). Based on the desired steady-state [O₂], these curves will aid in selecting films and optimizing packaging ratios for a wide range of packaging.
toes in MAP containing 3% to 6% O₂ can be kept 3 weeks at 20°C without reaching the pink stage (data not shown). The accompanying steady-state CO₂ concentrations in those packages usually ranged from 3% to 5%. No CO₂ injuries on fruit were observed in this study, either when fruit were in packages for up to 4 weeks or when ripened subsequently in air at 20°C.

Our results indicate that packaging variables necessary for a MAP to achieve the desired O₂ concentration can be predicted mathematically. Functions showing predicted steady-state O₂ concentrations for a range of packaging ratios (Fig. 3) is a new approach, and, in this study, was tested comprehensively on two films and with various package sizes and packaging ratios.

For predicting steady-state O₂ concentrations in packages of tomato at 20°C, the equations developed from O₂ depletion data fitted with second-order polynomials had excellent predictive power. Fitting a relatively simple model to the O₂ depletion data helped keep the final predictive equation from getting overly complex.

The strong predictive power of Eq. [9] (see Fig. 3) will give versatility to practical applications and answer many questions concerning designing MAP systems without the need for much time spent on testing and development. For example, Fig. 3 will allow packers to know immediately the appropriateness of films based on the packaging ratio of a MAP design. Suppose it is desired that a package achieve an O₂ concentration between 3% and 5% at a packaging ratio of about 1.0. Film B is clearly more appropriate than film A for this situation. Since permeability of selected films is often close to, but not exactly, the ideal value predicted, packaging ratio may be optimized by either varying film surface area or commodity weight to achieve the desired in-package O₂ concentrations.

Equation [9] can be used to make commercially useful predictions that will aid in selection of films and packaging ratios. For example, if one wanted to design a retail package of a specified size to hold a specified quantity of fruit, data such as those presented in Fig. 5 will help one to select a film with appropriate gas permeability based on the desired O₂ concentration. Alternatively, an appropriate packaging ratio also can be selected, based on permeability of a packaging film and the desired steady-state O₂ concentration from data such as those presented in Fig. 5.

Effects of temperature on in-package steady-state O₂ concentrations are important to know because packages will likely experience changes in temperature during distribution. A critical concern in transit is that increased temperature could lead to depletion of oxygen and the risk of fermentative reactions. In this study with tomato PEVA package, temperature changes from 20 to 28°C resulted in only a small increase in steady-state O₂ concentration (≈1.25%). This result suggests that the increase in respiration was largely offset by the increase in permeability of the film in this temperature range. A decrease in temperature from 28 to 10°C caused a >3.0% increase in steady-state O₂ concentration. This result indicates that a greater decrease in respiration rate than the decrease in film O₂ permeability occurred when the temperature was dropped from 28 to 10°C. A relatively large increase in steady-state O₂ concentration (i.e., 3%) would have the effect of decreasing the benefits of a MAP.

One limitation of the mathematical procedure is that it did not take into consideration the effect of CO₂ on O₂ consumption rate. Oxygen depletion data used for the derivation of the input variable RR₀ were collected in jars where CO₂ was allowed to accumulate. However, the excellent prediction results achieved suggests that the effect of CO₂ on O₂ consumption rate of mature-green tomato was negligible. This finding is in agreement with previous reports.
(Henig and Gilbert, 1975; Kubo et al., 1989). Reduction in O₂ consumption rate in response to CO₂ concentration up to 20% is very low, although CO₂ concentration above 9% decreased CO₂ evolution rate from 18 to 12 ml·kg⁻¹·h⁻¹ in tomato (Henig and Gilbert, 1975). Refinement of the input variable (RRO₂) in the prediction equation will become necessary for commodities where higher CO₂ concentrations significantly affect O₂ consumption rate.

In conclusion, appropriate packaging variables that will maximize the benefits of MAP for tomato can be predicted with relatively straightforward mathematical procedures. With the help of a computer program, rapid simulations and predictions will allow one to know the appropriate packaging design in a matter of minutes. Rapid testing of the suitability of specific films and designs may be conducted using an active modification technique (Gong and Corey, 1992). If large temperature fluctuations during handling and distribution are expected to occur, the dependence of in-package O₂ concentration on temperature should be evaluated and appropriate temperature control should be applied accordingly. Proper implementation of MAP for tomato will retard ripening processes and extend fruit shelf life, thereby facilitating handling and reducing waste.

**Literature Cited**

Anderson, M.G. and P.A. Paapst. 1983. Effect of cultivar, modified atmosphere and rapeseed oil on ripening and decay of mature-green tomatoes. Can. J. Plant Sci. 63:509–514.

Beaudry, R.M., A.C. Cameron, A. Shirazi, and D. Dostal-Lange. 1992. Modified-atmosphere packaging of blueberry fruit: Effect of temperature on package oxygen and carbon dioxide. J. Amer. Soc. Hort. Sci. 117:436–441.

Cameron, A.C. 1990. Modified atmosphere packaging: A novel approach for optimizing package oxygen and carbon dioxide. Proc. 5th Intl. CA Conf., 14–16 June 1990, Wenatchee, Wash.

Cameron, A.C., W. Boylan-Pett, and J. Lee. 1989. Design of modified atmosphere packaging systems: Modeling oxygen concentrations within sealed packages of tomato fruits. J. Food Sci. 54:1413–1416.

Cheng T.S. and R.L. Shewfelt. 1988. Effect of chilling exposure of tomatoes during subsequent ripening. J. Food Sci. 53:1160–1162.

Dennis, C., K.M. Browne, and F. Adamicki. 1979. Controlled atmosphere storage of tomatoes. Acta Hort. 93:75–83.

Geeson, J.D. and K.M. Browne, K. Maddison, J. Shepherd, and F. Guaraldi. 1985. Modified atmosphere packaging to extend the shelf life of tomatoes. J. Food Technol. 20:339–349.

Gong, S. 1992. Design of modified atmosphere packaging systems for fresh produce. PhD Diss. Univ. of Massachusetts, Amherst.

Gong, S. and K.A. Corey. 1992. Rapid testing of films for modified atmosphere packages using an active modification technique. HortTechnology 2:358–361.

Hayakawa K., Y.S. Henig, and S.G. Gilbert. 1975. Formulae for predicting gas exchange of fresh produce in polymeric packages. J. Food Sci. 40:186–191.

Henig, Y.S. and S.G. Gilbert. 1975. Computer analysis of the variables affecting respiration and quality of produce packaged in polymeric films. J. Food Sci. 40:1033–1035.

Hobson, G.E. 1987. Low-temperature injury and the storage of ripening tomatoes. J. Hort. Sci. 62:55–62.

Kader, A.A. 1980. Prevention of ripening in fruits by use of controlled atmospheres. Food Technol. 34:51–54.

Kubo Y., A. Inaba, and R. Nakamura. 1989. Effect of high CO₂ on respiration in various horticultural crops. J. Jpn. Soc. Hort. Sci. 58:731–736.

Nakhasi, S., D. Schlimme, and T. Solomos. 1991. Storage potential of tomatoes harvested at the breaker stage using modified atmosphere packaging. J. Food Sci. 56:55–59.

Parsons, C.S., R.E. Anderson, and R.W. Penney. 1970. Storage of mature green tomatoes in controlled atmospheres. J. Amer. Soc. Hort. Sci. 95:791–794.

Ryall, A.L. and W.J. Lipton. 1979. Handling, transportation and storage of fruits and vegetables. Vol. 1. Vegetables and melons. 2nd ed. AVI, Westport, Conn.

SAS Institute. 1985. SAS user’s guide: Statistics. Version 5. SAS Institute Inc., Cary, N.C.

Stenvers, S. and J. Bruinsma. 1975. Ripening of tomato fruits at reduced atmospheric and partial oxygen pressures. Nature (London) 253:532–533.

Yang, C.C. and M.S. Chinnan. 1987. Modeling of color development of tomatoes in modified atmosphere storage. Trans. Amer. Soc. Agr. Eng. 30:548–553.

Yang, C.C. and M.S. Chinnan. 1988. Computer modeling of gas compositions and color development of tomatoes stored in polymeric film. J. Food Sci. 53:869–872.