External and ‘Internal Factors Influence Fruit Tolerance to Low-oxygen Atmospheres

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Abstract. Fruits of ‘Bing’ cherry (Prunus avium L.), ‘Red Jim’ nectarine (Prunus persica L.), ‘Angeleno’ plum (Prunus salicina, L.), ‘Yellow Newtown’ and ‘Granny Smith’ apples (Malus domestica Borkh.), and ‘20th Century’ pear (Pyrus serotina L.) were treated with 0.25% or 0.02% O₂ (balance N₂) at 0, 5, or 10°C to study the effects of these insecticidal low-O₂ atmospheres on their postharvest physiology and quality attributes. Development of alcoholic off-flavor was associated with ethanol accumulation, which was the most common and important detrimental effect that limited fruit tolerance to low O₂. Relatively higher storage temperature (T), higher respiration rate (R), and greater resistance to gas diffusion (r) enhanced while relatively higher O₂ concentration (C) and higher soluble solids concentration (SSC) reduced off-flavor development. Using a SAS computer program to do multiple regression analysis with T, C, R, r, and SSC as variables, models were developed for prediction of fruit tolerance to insecticidal low-O₂ atmospheres. Comparison of fruit tolerances and published information on the times required to completely kill specific insects by O₂ levels at or below 1% suggests that low-O₂ atmospheres have a good potential for use as postharvest quarantine treatments for some fruits.

The potential of short-term exposure to O₂ levels < 1% and/or CO₂ levels >50% to replace chemical fumigation for postharvest insect control to meet quarantine requirements of fresh fruits and vegetables has recently been extensively investigated (Ali Niaze et al., 1989; Benshoter, 1987; Dentener et al., 1990; Kosiritrakun, 1989; Soderstrom et al., 1987, 1990). Controlled atmosphere (CA) treatments can be used for quarantine procedures only when the fresh commodities can tolerate low-O₂ and/or high-CO₂ conditions longer than the time required to completely kill the insects of concern. We have investigated tolerances of diverse fruits to insecticidal CA conditions (Ke and Kader, 1989, 1990; Ke et al., 1990, 1991a, b, and c). Chen et al. (1981) reported that sweet cherries stored in 0.5% to 1% O₂ at –1.1°C for 35 days maintained stem greenness, desirable fruit color, and a higher level of titratable acidity than those kept in air. Patterson (1982) showed that keeping sweet cherries in 1% O₂ at 0 to 1.7°C for 5 to 8 weeks maintained SCC and red pigmentation, but did not have a significant effect on firmness. Treatments with low O₂ and/or high CO₂ retarded softening and color changes and reduced respiration and ethylene production rates of peaches and nectarines (Smilanick and Fouse, 1989; Wang and Anderson, 1982). However, if fresh fruits were exposed to stress O₂ and/or CO₂ levels for a period longer than the time they could tolerate, detrimental effects such as abnormal ripening, flesh browning, and accumulation of ethanol and acetaldehyde occurred (Kader, 1986; Ke et al., 1991c; Smilanick and Fouse, 1989).

In this paper, we analyze important factors that influence fruit tolerance to low-O₂ atmospheres and determine whether conditions required for specific insect disinfestation are tolerated by the fruit species in question.

Materials and Methods

Materials and treatments. Fruits of ‘Bing’ cherry, ‘Red Jim’ nectarine, ‘Angeleno’ plum, ‘Yellow Newtown’ and ‘Granny Smith’ apples, and ‘20th Century’ pear were obtained on the day of harvest from commercial shippers in San Joaquin, Fresno, Monterey, San Joaquin, and Solano counties of California, respectively. They were transported in an air-conditioned car to our laboratory at the Univ. of California, Davis, where they were kept overnight at 0°C. Experiments were initiated the next morning. Overripe fruits and those with defects were culled and five to 20 good fruits were put into a 4-liter glass jar as one replicate. Three replicates were used per treatment in a flow-through system at a flow rate that maintained CO₂ concentration within the container <0.3%. In one series of experiments, the fruit samples were kept in air and in the insecticidal O₂ concentrations of 0.25% ± 0.02% or 0.02% (by mixing N₂ with air using needle valves to control flow rate of each gas) at 0, 5, or 10°C for 3 days before they were used for the determinations of respiration rate, internal CO₂ concentration, and resistance to gas diffusion. In another series of experiments, fruit samples were kept in the stated atmospheres at 0, 5, or 10°C for 7 to 45 days followed by storage in air at 0°C for 6 to 7 days to allow ethanol content to decrease. Then, the fruits were ripened in air at 20°C for 1 to several days before final quality evaluation. An exception was cherries, which were not transferred to 20°C since the fruits were ripe when harvested.

Gas analysis. The O₂ and CO₂ concentrations were measured by analysis of a 10-ml gas sample using an electrochemical O₂ analyzer (model S-3All, Applied Electrochemistry, Sunnyvale, Calif.) in series with an infrared CO₂ analyzer (model PIR-2000, Horiba Instrument, Irvine, Calif.). Respiration rate was estimated from the CO₂ concentration measured in the headspace of the jar holding the fruits, the flow rate used, and the fresh weight of the sample. Vacuum extraction was used to determine internal CO₂ concentration and resistance to gas diffusion (Ke

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Abbreviations: C, concentration; CA, controlled atmosphere; IS, intercellular spaces; R, respiration rate; r, resistance; RQ, respiratory quotient; SSC, soluble solids concentration; T, temperature.
and Kader, 1990). Resistance to CO₂ diffusion was calculated by the ratio: [(CO₂)₀₂ - (CO₂)ₐ]/CO₂ production rate. Intercellular space volume was estimated by determining the total amount of gases from the fruits after 30 min of vacuum extraction.

**Determination of quality attributes.** Three initial samples of five to 20 fruits each were evaluated for appearance, skin color, flesh firmness, SSC, pH, titratable acidity as percent malic acid, ethanol content, and flavor score. Similar measurements were done as part of the final quality evaluations. Appearance was scored using a subjective scale of 1 to 5 where 5 = excellent, 4 = good, 3 = fair, 2 = slight defects, 1 = severe defects. Skin color was measured with a Gardner XL-23 Tristimulus Colorimeter (Gardner Laboratory, Bethesda, Md.). Flesh firmness was measured as penetration force with a Univ. of California firmness tester (Western Industrial Supply Co., San Francisco) fitted with an 8-mm plunger tip. Fruit juice was extracted with a hand-press juicer. SSC was measured with an Abbe refractometer, and pH and titratable acidity were measured with an automatic titrator (Radiometer, Copenhagen, Denmark) with a PHM85 Precision pH meter, an AUB80 autoburette, a PRS12 Alpha printer, and a SAC80 sample changer.

**Determination of ethanol content.** Ethanol in fruit juice was measured using a HP5890A gas chromatograph (Hewlett Packard, Palo Alto, Calif.) as described by Ke et al. (1991b).

**Estimation of flavor score.** Flavor of three fruits per treatment was evaluated by tasting as previously described (Ke et al., 1991b) using a scale of 1 to 7 where 7 = excellent, 6 = good, 5 = fair, 4 = slight off-flavor, 3 = moderate off-flavor, 2 = severe off-flavor, and 1 = extreme off-flavor.

**Estimation of low O₂ injury.** Internal injury severity was visually estimated using a pretransformed scale of 1 to 5 according to the percentage of brown area of the fruit’s longitudinal section: 1 = no injury; 2 = slight injury, 1% to 15% of the area with browning; 3 = moderate injury, 16% to 50% browning; 4 = severe injury, 51% to 85% browning; 5 = extreme injury, 86% to 100% browning.

**Statistical analysis.** Data were treated for multiple comparisons by analysis of variance with least significant difference (LSD) between means determined at P = 0.05. The REG procedure (SAS Institute, 1985) was used for multiple regression analysis.

**Results and Discussion**

**Fruit quality.** ‘Bing’ cherries were ripe at harvest, as indicated by SSC (17%) and titratable acidity (0.84%). Exposure to 0.25% or 0.02% O₂ retarded darkening of the red pigment of the fruits, especially at 5C. There were no significant differences among treatments in overall appearance quality, SSC, pH, and titratable acidity. Decay was negligible and no low-O₂ injury was observed during the 35 days of storage at 0 or 5C.

Exposure of cherries to 0.25% or 0.02% O₂ resulted in accumulation of ethanol (Fig. 1 A and B), which was associated with a decrease in flavor score (Fig. 1 C and D). These effects were much more pronounced with 0.02% O₂. A flavor score of 4 (slight alcoholic off-flavor) or lower value rendered the fruit unacceptable in taste. Therefore, the number of days to reach a flavor score of 4 was considered as the tolerance limit (T₁) of the commodity to low-O₂ treatments. By linear extrapolation from Fig. 1 C and D, the tolerance limits from the experiments (T₂ₒ₂) were 25.3 and 21.3 days for 0.02% O₂ at 0 and 5C, respectively.

‘Red Jim’ nectarines were red when harvested and no signifi-
Fig. 2. Effects of storage temperature and O$_2$ level on ethanol content (EC) and flavor score of ‘Red Jim’ nectarines. The fruits were kept in air, 0.25% O$_2$ or 0.02% O$_2$ at 0 or 10°C for 7, 14, or 21 days followed by transfer to air at 0°C for 6 days and then to 20°C for 1 to 4 days. Flavor score was estimated using the same scale mentioned in the legend of Fig. 1. Vertical bars represent LSD values at $P = 0.05$.

Production rate, resistance to CO$_2$ diffusion, SSC and tolerance limits ($T_{le}$, based on occurrence of off-flavor) of ‘Bing’ cherries, ‘Red Jim’ nectarines, ‘Angeleno’ plums, “Yellow Newtown” and ‘Granny Smith’ apples, and ‘20th Century’ pears are summarized in Table 1.

Prediction of fruit tolerance to low O$_2$. Among the fruits we tested, ‘Red Jim’ nectarine and ‘20th Century’ pear were the only two commodities in which low-O$_2$ injury was observed during short-term exposure to 0.02% or 0.25% O$_2$ at 0 to 10°C. However, alcoholic off-flavor was noted in all the commodities tested after various durations of low-O$_2$ treatments.

Development of off-flavor in fruits is thought to be caused by accumulation of ethanol, acetaldehyde, ethyl acetate, and probably some other volatile compounds formed under anaerobic conditions. Ke et al. (1991b) indicated that flavor score and ethanol content have a logarithmic relationship and that fruit tolerance ($T_l$) to low O$_2$ could be predicted by the following equation:

$$T_l = E_o/V_e = (10^{0.228 \text{SSC}})/V_e$$  \[1\]

where $E_o$ is the threshold ethanol content for off-flavor detection and $V_e$ is the average ethanol accumulation rate per day under a low-O$_2$ treatment. This model is simple to use since only two variables (SSC and $V_e$) are involved, but it requires a relatively longer period for measuring ethanol accumulation rate.

Ethanol is a product of anaerobic respiration under limited O$_2$ supply. Internal O$_2$ concentration ($C_i$) for aerobic/anaerobic transition is a critical point. $C_i$ must be maintained higher than this transition point to prevent ethanol accumulation. If $C_i$ is lower than the transition point, anaerobic respiration rate and ethanol accumulation rate will be negatively correlated to $C_i$, and $T$, will be positively correlated to $C_i$. This relationship can be expressed by:

$$T_l \propto C_i$$  \[2\]

The relationship of resistance to O$_2$ diffusion ($r$), external O$_2$ Table 1. Tolerance limits from experiments ($T_{le}$) and predicted tolerance limits ($T_l$) to low O$_2$ by using temperature ($T$), O$_2$ concentration ($C$), respiration rate ($R$), resistance to CO$_2$ diffusion ($r_{CO_2}$ or $r$), and soluble solids concentration (SSC) of six commodities as variables. Both R and r were measured after 3 days of treatment and SSC was measured in ripe fruits.

| Commodity          | $T$ ($^\circ$C) | $C$ (%) | CO$_2$ production rate (mol kg$^{-1}$ h$^{-1}$) | $r$$_{CO_2}$ | SSC (%) | $T_{le}$ (days) | $T_l$ (days) | $T_{le} - T_l$ (days) |
|--------------------|----------------|---------|-----------------------------------------------|--------------|---------|----------------|-------------|-------------------|
| ‘Bing’ cherry      | 0              | 0.25    | 2.7                                           | 0.14         | 16.0    | 43.8           | 43.3        | 0.5               |
|                    | 0              | 0.02    | 3.4                                           | 0.13         | 16.0    | 25.3           | 28.0        | -2.7              |
|                    | 5              | 0.25    | 3.6                                           | 0.10         | 16.0    | 38.1           | 33.0        | 5.1               |
|                    | 5              | 0.02    | 4.3                                           | 0.11         | 16.0    | 21.3           | 24.4        | -3.1              |
| ‘Red Jim’ nectarine| 0              | 0.25    | 2.6                                           | 0.14         | 13.2    | 28.0           | 35.0        | -7.0              |
|                    | 10             | 0.25    | 9.0                                           | 0.07         | 13.2    | 13.0           | 11.1        | 1.9               |
|                    | 10             | 0.02    | 10.6                                          | 0.08         | 13.2    | 10.5           | 8.6         | 1.9               |
| ‘Angeleno’ plum    | 5              | 0.25    | 2.2                                           | 0.63         | 15.3    | 40.6           | 29.7        | 10.9              |
|                    | 5              | 0.02    | 3.2                                           | 0.46         | 15.3    | 31.6           | 21.6        | 10.0              |
|                    | 10             | 0.25    | 3.7                                           | 0.40         | 15.3    | 14.0           | 19.8        | -5.8              |
|                    | 10             | 0.02    | 4.5                                           | 0.41         | 15.3    | 9.4            | 17.9        | -8.5              |
| ‘Yellow Newtown’ apple | 5          | 0.25    | 2.7                                           | 2.0          | 13.4    | 11.3           | 17.2        | -5.9              |
|                    | 5              | 0.02    | 3.6                                           | 2.2          | 13.4    | 9.9            | 8.3         | 1.6               |
|                    | 10             | 0.25    | 6.2                                           | 1.5          | 13.4    | 8.2            | 7.7         | 0.5               |
|                    | 10             | 0.02    | 6.2                                           | 1.8          | 13.4    | 7.0            | 5.1         | 1.9               |
| ‘Granny Smith’ apple | 0            | 0.25    | 1.2                                           | 1.6          | 11.9    | 23.4           | 26.0        | -2.6              |
|                    | 0              | 0.02    | 1.4                                           | 1.7          | 11.9    | 11.9           | 10.5        | 1.4               |
|                    | 10             | 0.25    | 4.4                                           | 1.1          | 11.9    | 7.0            | 6.2         | 0.8               |
|                    | 10             | 0.02    | 4.2                                           | 1.1          | 11.9    | 5.0            | 5.0         | 0.0               |
| ‘20th Century’ pear | 0              | 0.25    | 0.8                                           | 0.23         | 10.7    | 35.0           | 28.4        | 6.6               |
|                    | 0              | 0.02    | 1.0                                           | 0.21         | 10.7    | 16.2           | 13.5        | 2.7               |
|                    | 5              | 0.25    | 1.6                                           | 0.21         | 10.7    | 13.1           | 18.1        | -5.0              |
|                    | 5              | 0.02    | 1.6                                           | 0.24         | 10.7    | 11.0           | 9.9         | 1.1               |

*Predicted by Eq. [6]: $T_l = -0.484 T + 64.6 C - 0.722 R - 4.20 r + 3.00 SSC - 5.90 T \times C - 18.2.$

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concentration ($C_o$), internal $O_2$ concentration, and $O_2$ consumption rate or respiration rate ($R$) can be expressed as:

$$r = \frac{C_o - C_l}{R}$$  \[3\]

Rearrangement of Eq. [3] gives:

$$C_l = C_o - Rr$$  \[4\]

Replacing Eq. [4] for $C_l$ in formula [2], then:

$$T_i = \frac{C_o - Rr}{T}$$  \[5\]

According to formula [5], $T_i$ could be influenced by $C_o$, $R$, and $r$. Since it is extremely difficult to determine $O_2$ consumption rate and resistance to $O_2$ diffusion ($rO_2$) at the extremely low $O_2$ concentrations (0.02% to 0.25%), we used $CO_2$ production rate and resistance to $CO_2$ diffusion ($rCO_2$) in the quantitative analysis when these replacements are permitted. Usually, $rO_2$ and $rCO_2$ are similar but not identical and the same is true for $O_2$ consumption rate and $CO_2$ production rate.

Oxygen concentration ($C_o$) is directly proportional to $T_i$. Since $Rr$ is always a positive value, $C_o$ must be higher than the aerobic/anaerobic transition point to provide enough $C_o$ to maintain aerobic respiration. If $Rr$ is relatively high, then higher external $O_2$ concentration is required to maintain $C_o$ level above the transition point to prevent ethanol accumulation. In the cases that $C_o$ is below the aerobic/anaerobic transition point, ethanol accumulates faster and $T_i$ increases as $C_o$ is raised. This relationship is clearly shown in Table 1 where 0.25% $O_2$ always gave higher $T_i$ values than those of 0.02% $O_2$ for the same commodity at the same temperature.

Under aerobic conditions, the respiratory quotient (RQ) is $\approx 1$ in most cases. Under anaerobic conditions, $CO_2$ production rate exceeds $O_2$ consumption rate resulting in an RQ value higher than 1. A commodity with a relatively high respiration rate ($R$) under low-$O_2$ requires a relatively high $C_o$ to maintain aerobic respiration. In cases where $C_o$ is lower than the aerobic/anaerobic transition point, ethanol accumulates faster and $T_i$ decreases as $R$ increases. According to formula [5], a commodity with a low respiration rate usually tolerates low $O_2$ better than one with a high rate if the other conditions are the same.

Resistance to gas diffusion ($r$) usually depends on the structure of the dermal system of the commodity; but postharvest treatments, such as waxing and film wrapping, can greatly increase $r$ values. A commodity with a high $r$ value would require a higher $C_o$ to maintain aerobic respiration than one with a low value. Under anaerobic conditions, a high $r$ would also limit the diffusion of ethanol out of the commodity, increasing $V_e$. Since $rO_2$ is usually positively correlated to $rCO_2$, the latter could be used for approximate analysis. According to formula [5], a commodity with a relatively high resistance to gas diffusion would be less tolerant to low $O_2$ than one with a lower resistance. The values of $r$ for the same commodity may also change during maturation. Ripe fruits usually have higher $r$ values and are more sensitive to low-$O_2$ treatments than mature-green fruits.

Storage temperature ($T$) can influence both $R$ and $r$. As $T$ was raised, respiration rate increased but resistance to gas diffusion decreased (Table 1). However, the effect of temperature on $R$ was greater than its effect on $r$. For example, as $T$ changed from 0°C to 10°C, $R$ changed by 3.0- to 4.3-fold, while $r$ changed by 1.4- to 2.0-fold (Table 1). Therefore, as temperature increases, the tolerance to low $O_2$ decreases. Raising $T$ greatly increases $R$ and reduces $O_2$ solubility in solution and, therefore, a higher $C_o$ is required to maintain aerobic respiration. Meanwhile, there is a strong temperature/$O_2$ concentration interaction. $T$ was 1.5 to 2.5 times higher at 0.25% $O_2$ than at 0.02% at 0°C, 1.4 to 2.0 times at 5°C, and 1.1 to 1.5 times higher at 10°C (Table 1).

The SSC of the commodity when ripe was not substantially influenced by the $O_2$ level or temperature during short-term storage treatments. Commodities with high SSC values, such as cherry and plum, generally were more tolerant to low $O_2$ than those with lower SSC values (Table 1).

Ethanol is very soluble in water; its diffusion through intercellular spaces (IS) is much faster than through a liquid phase. The abundance of IS in a commodity may influence ethanol diffusion. The IS volumes for ‘20th Century’ pear, ‘Bing’ cherry, ‘Angeleno’ plum, ‘Red Jim’ nectarine, ‘Granny smith’ apple, and ‘Yellow Newtown’ apple were 3.3%, 3.6%, 4.2%, 6.7%, 14%, and 16%, respectively. However, statistical analysis did not indicate a consistent and significant influence of IS on $T_i$, probably because IS is related to $r$ or because $r$ masks the effect of IS. In fruits, such as apples and oranges (*Citrus sinensis* (L.) Osb.), skin is the major barrier for gas diffusion. However, in fruits with very small IS volumes, such as Asian pear, flesh resistance may make a substantial contribution to $r$.

Based on multiple regression analysis (REG procedure, SAS, 1985) of data from Table 1, a model of important factors influencing fruit tolerance to low $O_2$ is generated:

$$T_i = -0.484 T + 64.6 C - 0.722 R - 4.20 r + 3.00 SSC - 5.90 T \times C - 18.2 \quad \text{[6]}$$

where $T$ = temperature used, $C$ = external $O_2$ concentration used, $R$ = $CO_2$ production rate, $r$ = resistance to $CO_2$ diffusion, and $SSC$ = soluble solids content. Eq. [6] indicates that relatively high temperature, respiration rate, and resistance to gas diffusion reduce fruit tolerance to low-$O_2$ atmospheres; relatively high $O_2$ concentration and SSC increase fruit tolerance. Interaction between temperature and $O_2$ concentration is also involved in this model.

A correlation coefficient of 0.902 was obtained for Eq. [6] at $P < 0.0001$. This model could reasonably predict $T_i$ in most cases and the average difference between observed tolerance and predicted tolerance is $\approx 4$ days (Table 1). In Eq. [6], $T$ and $C$ are predetermined or specified, $R$ and $r$ are measured after 3 days of low-$O_2$ treatment, and SSC is commodity specific that is measured after the fruits are allowed to ripen.

It should be noted that this regression model is limited to $T$ of 0, 5, and 10°C and C of 0.25% and 0.02%. For other temperatures and $O_2$ concentrations, this model should be used with care or modified as needed.

Since $T$ influences both $R$ and $r$ (Table 1), variables $R$ and $r$ are not completely independent in Eq. [6]. The interaction between $T$ and $C$ also reduces the accuracy of using this model for predicting $T_i$. To improve prediction accuracy, individual models for each temperature (0, 5, and 10°C) were developed as follows:

For 0°C

$$T_i = 54.2 C - 12.2 R - 7.23 r + 6.56 S - 39.8 \quad \text{[7]}$$

For Eq. [7], correlation coefficient = 0.984, $P = 0.013$, average difference between $T_{le}$ and $T_i = 1.6$ days (Table 2).

For 5°C

$$T_i = 14.5 C - 9.90 R - 1.07 r + 7.68 S - 56.0 \quad \text{[8]}$$

For Eq. [8], correlation coefficient = 0.986, $P = 0.011$, average difference between $T_{le}$ and $T_i = 1.6$ days (Table 2).
Table 2. Comparison of tolerance limits from experiments (T_{le}) and predicted tolerance limits (T_{l}) to low O_{2} by using O_{2} concentration (C), respiration rate (R), resistance to CO_{2} diffusion (r), and soluble solids concentration (SSC) of six commodities as variables at specified temperatures.

| Commodity       | Temp (°C) | O_{2} (%) | T_{le} (days) | T_{l} (days) | O_{2} model | CO_{2} model | 10C model |
|-----------------|-----------|-----------|---------------|--------------|-------------|--------------|-----------|
| ‘Bing’ cherry   | 0         | 0.25      | 43.8          | 44.6         | -0.8        |              |           |
|                 | 0         | 0.02      | 25.3          | 23.7         | 1.6         |              |           |
|                 | 5         | 0.25      | 38.1          |              |             |              |           |
|                 | 5         | 0.02      | 21.3          |              |             |              |           |
| ‘Red Jim’ nectarine | 0     | 0.25      | 28.0          | 27.5         | 0.5         |              |           |
|                 | 0         | 0.02      | 14.0          | 16.1         | -2.1        |              |           |
|                 | 10        | 0.25      | 13.0          |              |             |              | 12.1      |
|                 | 10        | 0.02      | 10.5          |              |             |              | 9.7       |
| ‘Angeleno’ plum | 5         | 0.25      | 40.6          | 42.7         | -2.1        |              |           |
|                 | 5         | 0.02      | 31.6          | 29.7         | 1.9         |              |           |
|                 | 10        | 0.25      | 14.0          |              |             |              | 13.5      |
|                 | 10        | 0.02      | 9.4           |              |             |              | 11.1      |
| ‘Yellow Newtown’ apple | 5   | 0.25      | 11.3          | 11.8         | -0.5        |              |           |
|                 | 5         | 0.02      | 9.9           | 9.2          | 0.7         |              |           |
|                 | 10        | 0.25      | 8.2           |              |             |              | 8.6       |
|                 | 10        | 0.02      | 7.0           |              |             |              | 5.4       |
| ‘Granny Smith’ apple | 0  | 0.25      | 23.4          | 25.6         | -2.2        |              |           |
|                 | 0         | 0.02      | 11.9          | 9.9          | 2.0         |              |           |
|                 | 10        | 0.25      | 7.0           |              |             |              | 8.0       |
|                 | 10        | 0.02      | 5.0           |              |             |              | 5.7       |
| ‘20th Century’ pear | 0  | 0.25      | 35.0          | 32.5         | 2.5         |              |           |
|                 | 0         | 0.02      | 16.2          | 17.7         | -1.5        |              |           |
|                 | 5         | 0.25      | 13.1          |              |             |              | 13.8      |
|                 | 5         | 0.02      | 11.0          |              |             |              | 10.4      |

For 10C

T_{l} = 11.4 C + 0.352 R - 1.88 r + 1.30 S - 10.4 [9]

For Eq. [9], correlation coefficient = 0.963, P = 0.016, average difference between T_{le} and T_{l} = 0.7 days. In Eq. [9], the regression coefficient of 0.352 is small compared to those of C, r, and SSC and statistically not significant (P = 0.224). Since the influence of R on T should be negative according to formula [5], the involvement of R data in the model did not appear to be appropriate and it was removed to obtain the following model:

T_{l} = 10.3 C - 2.60 r + 1.06 S - 4.35 [10]

For Eq. [10], correlation coefficient = 0.934, P = 0.029, average difference between T_{le} and T_{l} = 0.9 days (Table 2).

Comparing Eq. [6] to Eqs. [7], [8], and [10], it appears that the prediction accuracy is increased by developing models for each temperature.

Comparison of fruit tolerance and insect disinfestation by low O_{2}. We recently summarized the limited published information about the time required to completely kill specific insects at specified O_{2} and CO_{2} concentrations and temperatures (Ke and Kader, 1992). Comparing fruit tolerances to such conditions, there are many cases where insecticidal atmospheres are tolerated by fruits. For example, San Jose scale (Quadraspidiotus perniciasus), apple rust mite (Acculus schlechtendali), European red mite (Panonychus ulmi), and codling moth (Cydia pomonella) could be killed by CA without detrimental effects on apples (Gaunce et al., 1982; Ke and Kader, 1989; Lidster et al., 1981, 1984; Morgan and Gaunce, 1975). Similarly, Caribbean fruit fly (Anastrepha suspensa) in citrus, thrips (Frankliniella occidentials) in strawberry, and leafroller (Planotortrix exces-sana) and mealy bug (Pseudococcus longispinus) in persimmon reach 100% mortality before detrimental effects are observed in the host commodities (Aharoni et al., 1979, 1981; Benshoter, 1987; Dentener et al., 1990; Ke and Kader, 1990; Ke et al., 1991a). However, apple maggot (Rhagoletis pomonella) is not completely killed before detrimental effects occur in apple under low-O_{2} treatment at 0 or 20C (Ali Niazee et al., 1989; Ke et al., 1991b; Kosittrakun, 1989). For nectarine, 0.5% O_{2} at 25C was not feasible for control of codling moth because detrimental effects were observed in the host fruits after 3 days of low-O_{2} treatment (Soderstrom et al., 1987). Thus, CA appears to have a potential as a replacement to chemicals for postharvest insect disinfestation in some commodities and some insects.

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