PREVENTION OF RIPENING IN FRUITS
BY USE OF CONTROLLED ATMOSPHERES

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ONE OF THE MAJOR BENEFITS of controlled atmospheres is the prevention or retardation of fruit senescence (ripening) and associated biochemical and physiological changes. Fruit ripening includes a complex of changes, most of which are quite likely biochemically independent of one another, that transform the mature but unripe fruit into an overripe and clearly senescent fruit. Pratt (1975) listed the following phenomena which may occur during the ripening of fleshy fruits:

1. Seed maturation.
2. Color change:
   a. Destruction of chlorophyll.
   b. Revelation of carotenoids (orange and yellow colors).
   c. Synthesis of carotenoids (red color of tomato).
   d. Synthesis of anthocyanins (red and blue colors).
3. Abscission.
4. Change in respiration rate:
   a. To satisfy the energy requirements of other changes.
   b. To reflect deterioration of rate controls.
   c. In response to excess ethylene.
   d. In relation to new enzyme activities.
5. Change in rate of ethylene production:
   a. To initiate ripening.
   b. Excess ethylene production as a phenomenon of senescence.
6. Change in tissue permeability.
7. Softening—changes in pectic composition.
8. Change in carbohydrate composition:
   a. Starch converted to sugar.
   b. Interconversion of sugars.
9. Protein changes:
   a. Quantitative.
   b. Qualitative:
      (1) Enzyme synthesis.
      (2) Changes in DNA and RNA.
10. Production of volatile compounds.
11. Development of wax on skin.
12. Organic acid changes:
    a. Absolute changes in amounts present.
    b. Relative—change in flavor relative to sweetness.

INTERRELATED PHENOMENA

Many of the above phenomena occur concurrently and are interrelated. Ethylene (C₂H₄), a natural plant hormone, plays a central role in the initiation of ripening. It is physiologically active in trace amounts (0.1 ppm). The capacity to produce C₂H₄ varies greatly among fruits, as shown in Table 1. The excess C₂H₄ produced by fruits with moderate-to-high production rates is a phenomenon of senescence in fruits which exhibit a climacteric rise in respiration. Elevated carbon dioxide levels can inhibit, promote, or have no effect on C₂H₄ production by fruits (Abeles, 1973). CO₂ has been shown to be a competitive inhibitor of C₂H₄ action (Burg and Burg, 1967; 1969)—it delays fruit ripening by displacing C₂H₄ from its receptor site.

<table>
<thead>
<tr>
<th>Ethylene production rate (μL/kg·hr at 20°C)</th>
<th>Fruits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low: 0.01-0.1</td>
<td>Cherry, citrus, grape, pomegranate, strawberry</td>
</tr>
<tr>
<td>Low: 0.1-1.0</td>
<td>Blueberry, Kiwifruit, papaya, persea, pineapple, raspberry</td>
</tr>
<tr>
<td>Moderate: 1.0-10.0</td>
<td>Banana, fig, honeydew melons, mango, tomato</td>
</tr>
<tr>
<td>High: 10.0-100.0</td>
<td>Apple, apricot, avocado, canteleipple, nectarine, papaya, peach, pear, plum</td>
</tr>
<tr>
<td>Very high: &gt;100.0</td>
<td>Cherimoya, mamey apple, passion fruit, sapote</td>
</tr>
</tbody>
</table>

Burg and Burg (1967; 1969) also demonstrated that oxygen is required for C₂H₄ action and suggested that binding of C₂H₄ to the receptor site is also impeded when O₂ concentration is lowered below about 8%. C₂H₄ production is also reduced at such O₂ levels—at 2.5% O₂, C₂H₄ production is halved. Thus, low O₂ retards fruit ripening by inhibiting both production and action of C₂H₄. Recently, Adams and Yang (1979) reported that O₂ was required for the conversion of 1-amino-cyclopropane-1-carboxylic acid to C₂H₄, which is the final step in ethylene biosynthesis from methionine.

The effects of O₂ on prevention or delay of ripening can be, at least partially, overcome by the addition of C₂H₄. Quazi and Freebairn (1970) showed that adding C₂H₄ to bananas held under 0.5-5% O₂ initiated ripening. Reduced O₂ atmospheres are generally more effective in prevention of ripening on preclimacteric fruits, in which C₂H₄ production has not been initiated, than on more-mature fruits which have begun their C₂H₄ production.

Temperature is the most effective environmental factor in prevention of fruit ripening. Ripening and C₂H₄ production rates increase with increase in temperature between 0 and 25°C; temperatures above 25°C inhibit both C₂H₄ production and ripening of most fruits. To delay ripening, fruits should be held as close to 0°C as possible. However, some fruits, especially those from tropical and subtropical origin, suffer chilling injury at temperatures above their freezing point but below a specific critical temperature (5-15°C, depending on commodity, cultivar, and duration). The use of controlled atmospheres as a supplement to proper temperature maintenance to delay ripening is consequently more effective for chilling-sensitive fruits, but it is generally beneficial for all fruits.

EFFECTS OF CONTROLLED ATMOSPHERES

Of the various beneficial effects of controlled atmospheres (CA) on fruits, prevention of ripening processes is the most important. Out of more than 3,000 reports on CA (Morris et al., 1971; Murr et al., 1974; Kader and Morris, 1977a), more than half include some aspect of delaying ripening processes in fruits; apples have received the most attention. Several recent reviews (Isenberg, 1979; Lipton, 1975; Smock, 1979), chapters in books (Ryall and Lipton, 1979; Ryall and Pentzer, 1974; Fantastico, 1975), and a
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conference proceedings (Dewey, 1977) have covered some aspects of CA effects on fruits.

Reducing O₂, concentrations below 8% and/or elevating CO₂ concentrations above 1% retards fruit ripening. The lower the O₂ level and the higher the CO₂ level, the more retardation of ripening. However, there are limits beyond which physiological injury will outweigh the benefits from ripening prevention. Kader and Morris (1977b) pointed out that 2% O₂ is the lower limit tolerated by most fruits. Below this O₂ level, anaerobic respiration may result in the development of off-flavors and off-colors. Fruits exposed to such low O₂ levels may also lose their ability to attain uniform ripening and controlled atmospheres (CA). Tolerance limits for elevated O₂ vary greatly among fruits and among cultivars of a given fruit species. While most fruits may tolerate up to 5% CO₂, some fruits may show CO₂ injury at this level. Differences in tolerance to elevated CO₂ among apple cultivars are reflected in their recommended CA conditions (Table 2). Some fruits, such as sweet cherries and strawberries, not only tolerate 10-20% CO₂, but also benefit by such CO₂ levels.

Reduced O₂ and/or elevated CO₂ delays fruit ripening, reduces respiration and ethylene production rates, retards softening, and slows down the compositional changes associated with ripening. Prevention or delay of ripening in fruits thus has an indirect effect on decay incidence, since ripe fruits are more susceptible to attack by postharvest pathogens. The above-mentioned benefits of CA translate into extension of storage life, maintenance of quality, and reduction of postharvest losses.

Delaying fruit ripening by CA for a short duration (1-4 weeks), depending on the fruit, is not likely to have detrimental effect on flavor quality, whether the fruit is consumed fresh or processed (Claypool, 1973; Claypool and Davis, 1959; Claypool and Pangborn, 1972; Kader et al., 1976b). However, extended holding (more than 4 weeks) under CA may result in reduced flavor quality after removal from CA and ripening. Apples and pears are exceptions to this generalization, since they can be held under CA for several months without significant loss in flavor quality. Mitchell (1979) found that a CA of 2% O₂, 5% CO₂ delayed softening and retarded starch-to-sugar conversion in Kiwifruit for up to 6 mo at 0°C. These fruits ripened normally after removal from CA and attained good eating quality.

A successful CA treatment is one which will prevent or at least delay ripening processes in the fruit without any detrimental effects on their ripening and quality after removal from CA conditions. Thus, it is imperative that any CA treatment that proves to be effective in delaying ripening and extending storage life be evaluated as to its possible effects on quality attributes (appearance, texture, flavor, and nutritional value) of the fruit.

CURRENT CA USE AND POSSIBLE CHANGES

After 50 years of research and development, large-scale use of CA is still limited to long-term storage of apples and pears. CA (or modified atmosphere, MA) during transport has been used for several other fruits, namely, strawberries, sweet cherries, and bananas. A summary of recommended CA conditions during transport and/or storage of fruits is included in Table 3; also included are an estimate of potential benefits and the extent of current commercial use. It should be remembered that optimum CA conditions for any commodity depend upon maturity stage at picking, temperature and duration of storage, and interactions among various components of the atmosphere (O₂, CO₂, C.H., etc.).

There is no doubt that some of the recommended CA combinations shown in Table 3 will be changed as more research is completed. The following are some possible changes:

**Hypobaric, or Low-Pressure, Systems** may provide new opportunities for CA use on some fruits for which reduced O₂ is the effective CA treatment. Such systems have two advantages over conventional CA, namely, continuous removal of C.H., and more exact O₂ control which would allow the use of lower O₂ tensions than is feasible with CA without the danger of anaerobic respiration. For more information about low-pressure storage, see Lougheed et al., 1978; Mermelstein, 1979, and Janmieson 1980.

**Ethylene Removal from CA Storage**. The evidence is now clear that ethylene removal from CA storage rooms results in better firmness retention in apples, provided that the fruits are picked preclimacteric and are immediately placed under CA, and provided that C.H., is almost completely scrubbed out (Forshyth et al., 1979; Khee et al., 1976, Lu, 1977; Lougheed et al., 1973). Ethylene removal may also result in reduced respiration rate and in reduced production of other volatiles (ethanol, acetaldehyde, ethyl acetate, etc.) by the fruits. Mitchell (1979) found that removal of C.H., from CA storage was very beneficial in delaying softening of Kiwifruit. The benefits of C.H., removal have been also demonstrated for avocados and other fruits.

**Pre-CA Storage Treatments with CO₂**. Cusey and Olsen (1977) recommended storing 'Golden Delicious' apples under 10-20% CO₂ for 10-15 days immediately following harvest, before placing them under CA. Such treatment resulted in better retention of firmness (delayed softening) and reduced loss of acidity with no minimal CO₂ injury. However, similar treatments on other cultivars or with 'Golden Delicious' from other production areas resulted in more CO₂ injury than benefit (Smock, 1979).

**Use of Carbon Monoxide**. The addition of CO to CA may improve the potential for benefit for some fruits. Burg and Burg (1969) reported that CO, which exerts its biocidal effects by binding to metal-containing enzymes, can replace C.H., in all of its functions. Solomos and Laties (1973) reported that 0.1% CO in air caused a rapid onset of the respiratory climacteric, C.H., production, and ripening of avocados and bananas. Similar results with mature-green tomatoes were reported by Kader et al. (1977).

Recently, there has been an increasing interest in using CO because of its effectiveness at 5-10% in inhibition of decay on fruits (Woodruff, 1977; Kader et al., 1977; 1984; El-Goarani and Sommer, 1979). CO added to CA (low O₂, and/or elevated CO₂) has been found to be more effective in delay control than CO added to air. Kader et al. (1978) reported that 5-10% CO + air treatments increased CO and C.H., production rates and hastened ripening of mature-green tomatoes, but did not affect ripening rate of fruits picked partially ripe. When CO was combined with 4% O₂, it had no effect on ripening of mature-green or partially ripe fruits. Thus, 5-10% CO can be a useful supplement to low-O₂ atmospheres during transit and/or storage of some fruits to reduce decay incidence and severity without any undesirable effects on ripening.

**CONCLUSIONS**

The following conclusions concerning controlled atmospheres can be reached:

1. Prevention of ripening and associated changes in fruits

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Production area</th>
<th>Temperature (°C)</th>
<th>% O₂</th>
<th>% CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jonathan</td>
<td>Eastern and Midwestern states</td>
<td>2.2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>McIntosh</td>
<td>Eastern and Midwestern states</td>
<td>2.3</td>
<td>2.3</td>
<td>3</td>
</tr>
<tr>
<td>Newtown</td>
<td>California</td>
<td>4.4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Delicieux, Golden Delicious</td>
<td>Oregon</td>
<td>2.2</td>
<td>2.2</td>
<td>3</td>
</tr>
<tr>
<td>Rome Beauty, Winesap, and other cultivars</td>
<td>All areas</td>
<td>-1 to 0</td>
<td>2.3</td>
<td>1.3</td>
</tr>
</tbody>
</table>

*Adapted from Blanpied (1977) and Porritt (1977)*

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### Table 3—RECOMMENDED CA CONDITIONS during transport and/or storage of fruits, their potential for benefit, and the extent of commercial use

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Temperature range°C</th>
<th>CA % O₂</th>
<th>% CO₂</th>
<th>Potential for benefit</th>
<th>Extent of commercial use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deciduous tree fruits</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apple</td>
<td>0-5</td>
<td>2-3</td>
<td>1-2</td>
<td>Excellent</td>
<td>About 40% of U.S. production is stored under CA</td>
</tr>
<tr>
<td>Apricot</td>
<td>0-5</td>
<td>2-3</td>
<td>2-3</td>
<td>Fair</td>
<td>No commercial use</td>
</tr>
<tr>
<td>Cherry, sweet</td>
<td>0-5</td>
<td>3-10</td>
<td>10-12</td>
<td>Good</td>
<td>Some commercial use (pallet covers or box liners)</td>
</tr>
<tr>
<td>Fig</td>
<td>0-5</td>
<td>5</td>
<td>15</td>
<td>Good</td>
<td>Limited commercial use</td>
</tr>
<tr>
<td>Grape</td>
<td>0-5</td>
<td>—</td>
<td>—</td>
<td>Slight or none</td>
<td>(No commercial use; incompatible with SO₂ fumigation)</td>
</tr>
<tr>
<td>Kiwi fruit</td>
<td>0-5</td>
<td>2</td>
<td>5</td>
<td>Excellent</td>
<td>Limited commercial use</td>
</tr>
<tr>
<td>Nectarine</td>
<td>0-5</td>
<td>1-2</td>
<td>5</td>
<td>Good</td>
<td>Limited commercial use</td>
</tr>
<tr>
<td>Peach</td>
<td>0-5</td>
<td>1-2</td>
<td>5</td>
<td>Good</td>
<td>Limited commercial use</td>
</tr>
<tr>
<td>Pear</td>
<td>0-5</td>
<td>2-3</td>
<td>0-1</td>
<td>Excellent</td>
<td>Limited commercial use</td>
</tr>
<tr>
<td>Persimmon</td>
<td>0-5</td>
<td>3-5</td>
<td>5-8</td>
<td>Fair</td>
<td>No commercial use</td>
</tr>
<tr>
<td>Plum and prune</td>
<td>0-5</td>
<td>1-2</td>
<td>0-5</td>
<td>Good</td>
<td>No commercial use</td>
</tr>
<tr>
<td>Strawberry</td>
<td>0-5</td>
<td>10</td>
<td>15-20</td>
<td>Excellent</td>
<td>Increasing use during transit</td>
</tr>
<tr>
<td><strong>Subtropical and tropical fruits</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avocado</td>
<td>5-13</td>
<td>2-5</td>
<td>3-10</td>
<td>Good</td>
<td>Limited commercial use</td>
</tr>
<tr>
<td>Banana</td>
<td>12-15</td>
<td>2-5</td>
<td>2-5</td>
<td>Excellent</td>
<td>Some commercial use</td>
</tr>
<tr>
<td>Grapefruit</td>
<td>10-15</td>
<td>3-10</td>
<td>5-10</td>
<td>Fair</td>
<td>No commercial use</td>
</tr>
<tr>
<td>Lemon</td>
<td>10-15</td>
<td>5</td>
<td>0-5</td>
<td>Good</td>
<td>Limited commercial use</td>
</tr>
<tr>
<td>Lime</td>
<td>10-15</td>
<td>5</td>
<td>0-10</td>
<td>Good</td>
<td>Limited commercial use</td>
</tr>
<tr>
<td>Orange</td>
<td>8-12</td>
<td>2-5</td>
<td>5-10</td>
<td>Fair</td>
<td>No commercial use</td>
</tr>
<tr>
<td>Mango</td>
<td>10-15</td>
<td>10</td>
<td>5</td>
<td>Fair</td>
<td>No commercial use</td>
</tr>
<tr>
<td>Papaya</td>
<td>10-15</td>
<td>10</td>
<td>5</td>
<td>Fair</td>
<td>No commercial use</td>
</tr>
<tr>
<td>Pineapple</td>
<td>10-15</td>
<td>10</td>
<td>10</td>
<td>Fair</td>
<td>No commercial use</td>
</tr>
<tr>
<td><strong>Vegetable fruits</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cantaloupe</td>
<td>5-10</td>
<td>3-5</td>
<td>0-10</td>
<td>Good</td>
<td>Limited commercial use</td>
</tr>
<tr>
<td>Honeydew</td>
<td>10-12</td>
<td>3-5</td>
<td>0</td>
<td>No</td>
<td>Commercial use</td>
</tr>
<tr>
<td>melons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peppers, Bell</td>
<td>8-12</td>
<td>3-5</td>
<td>0</td>
<td>Fair</td>
<td>Limited commercial use</td>
</tr>
<tr>
<td>Peppers, chili</td>
<td>8-12</td>
<td>3-5</td>
<td>0</td>
<td>Fair</td>
<td>Limited commercial use</td>
</tr>
<tr>
<td>Tomatoes, mature-green</td>
<td>12-20</td>
<td>3-5</td>
<td>0</td>
<td>Good</td>
<td>Limited commercial use</td>
</tr>
<tr>
<td>Tomatoes, partially ripe</td>
<td>8-12</td>
<td>3-5</td>
<td>0</td>
<td>No</td>
<td>Commercial use</td>
</tr>
</tbody>
</table>

1. Usual and/or recommended range. A relative humidity of 85-95% is recommended.
2. Best CA combination may vary among cultivars and according to storage temperature and duration.
3. Comments about use refer to domestic marketing only; many of these commodities are shipped under MA for export marketing.
4. Adapted in part from Anderson and Hardenberg (1977), Mellenhuth (1977), and Ryall and Pentzer (1974).

is one of the main benefits of controlled atmospheres.

2. O₂ concentration has to be lowered below 8% to influence fruit ripening, and the lower the O₂ concentration the greater the effect.

3. Lowering O₂ levels below about 2% can be injurious to fruits because of anaerobic respiration and potential development of off-flavors and off-odors.

4. Elevated CO₂ levels retard fruit ripening; but at levels which can be tolerated by most fruits (<5%), CO₂ is generally less effective in prevention of ripening than reduced O₂.

5. Fruits and even cultivars within a given fruit vary greatly in their tolerance to elevated CO₂. Physiological injuries resulting from elevated CO₂ and/or reduced O₂ beyond tolerance limits include impairment of ripening upon removal from CA.

6. The effectiveness of CA in prevention of fruit ripening depends upon commodity, cultivar, maturity stage at harvest, temperature, duration, and atmospheric composition.

7. CA influences fruit ripening via its effects on C.H₄ production by the fruit and its responses to C.H₄.

8. If added CO₂ is to be used for decay control, it should be used with low O₂ to counteract its possible stimulation of fruit ripening, since CO₂ mimics C.H₄ effects.

9. Removal and/or exclusion of C.H₄ from the environment around fruits under CA is beneficial in terms of delaying fruit ripening and softening, even at low temperatures (0-5°C).

10. Pre-CA treatment storage with elevated (10-20%) CO₂ for 1-4 weeks have been shown to have an additional beneficial effect on delaying fruit ripening and softening; but for some cultivars, CO₂ injury exceeds the benefits.

**REFERENCES**


Claypool, L.L. and Fangborn, R.M. 1972. Influence of controlled atmosphere...
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