Review

Ripening of European pears: The chilling dilemma

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ABSTRACT

The majority of European pears (Pyrus communis L.) show at some extent resistance to ripening after harvest. Low temperatures and/or ethylene treatments have to be applied to counteract this behavior. This review provides the main protocols that have been used experimentally to ripen European pears grown in the U.S. and summarizes important aspects to understand the ripening physiology of this fruit. Many factors interacting with pear ripening are discussed including, cold storage, controlled atmosphere storage, ethylene treatment, cultivar differences, preharvest temperature, growing region, harvest maturity, storage time and ripening temperature, cooling and warming of fruits, treatments to inhibit ripening, and plant growth regulators.

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Most European pears (Pyrus communis L.), unlike other climacteric fruit, possess varying degrees of resistance to ripening at harvest even when harvested at the appropriate maturity, and require a period of chilling and/or ethylene exposure to ripen properly. This resistance to ripening poses a number of practical challenges for the pear industry in preparing their fruit for market, and therein rests the dilemma. The biochemical basis for this resistance and the specific requirements for cold and/or ethylene exposure are not well described or understood.

Pears ripened on the tree generally do not develop the characteristic buttery and juicy texture required for marketing and consumption (Murayama et al., 1998). It has been demonstrated that ripe ‘Bartlett’ pears out-sell unripe pears by a ratio of three to one (California Pear Advisory Board, 2004). In addition, studies conducted across the U.S. showed that ‘d’Anjou’ pears treated with exogenous ethylene prior to marketing out-sold pears not treated with ethylene by 16% (Pear Bureau Northwest, 2002). This increase in marketability may be due to the perception of aromatic volatiles by consumers in ripened fruit on display at the market as well as the improved taste of the ripened pears (Rapparini and Predieri, 2003). There is an increasing interest in marketing European pears in a partially ripened stage. Detailed ripening protocols have been developed for some cultivars of pears, but not for others, and the scientific basis of some of these protocols is unclear.

This review summarizes the available research results related to European pear fruit ripening, from expression of ethylene biosynthetic genes to commercial methods for controlling the rate and uniformity of ripening. Physiological studies that increase our understanding of the underlying mechanisms of pear ripening, and the influence of preharvest and postharvest factors are presented. A listing of current ripening protocols involving cold storage and/or ethylene treatments is provided for several pear cultivars.

1. Effect of cold storage

Proper temperature during storage is the most important factor for maintenance of high quality pear fruit during postharvest management. In European pears, temperatures ranging from –1 to 10 °C (low temperature conditioning) also play a crucial role in the stimulation of ethylene biosynthesis during subsequent ripening at room temperature (Sfakiotakis and Dilley, 1974; Chen et al., 1983; Knee et al., 1983; Blankenship and Richardson, 1985; Knee, 1987; Gerasopoulos and Richardson, 1997a,b; Lara and Vendrell, 1998; Agar et al., 2000a; Miró et al., 2001). However, for long-term storage of most pear cultivars, the quality and storage life are diminished by even a slightly elevated storage temperature above the opti-
mum (−1 to 0 °C) (Richardson and Kupferman, 1997). Porritt (1964) found that the storage life of ‘d’Anjou’ and ‘Bartlett’ pear was 35 and 40% greater at −1 °C than at 0 °C, respectively, which illustrates the impact of temperature management on storage life.

The length of cold storage after harvest also has a significant relationship with ethylene biosynthesis and the minimum chilling period required for normal ripening varies among pear cultivars (Table 1). Mitcham et al. (2000, 2006) found that ‘Bartlett’ pears require 14–21 d exposure to cold temperatures (−1 to 0 °C) to ripen normally if harvested at 76–84 N, whereas ‘d’Anjou’ fruit required 25–30, 45 or 60 d cold storage if harvested at <58, 58–62, or 62–67 N, respectively (Klahre et al., 1987). Furthermore, ‘Comice’ fruit required approximately 25–31 d of cold storage (Sugar and Basile, 2006) when harvested at 53–58 N, and ‘Bosc’ fruit required less than 7 or 10 d when harvested at 53–58 N or 58–62 N, respectively (Chen and Mellenthin, 1982). Sugar (unpublished data) determined that approximately 2 weeks cold storage period was required for ‘Bosc’ pears to ripen normally when harvested in Southern Oregon between 53 and 71 N.

It has been shown that time in cold storage can also influence eating quality. Elgar et al. (1997) studied the effect of harvest maturity and length of the cold storage period on the quality of ripened fruit in ‘Bosc’ and ‘Comice’. Ripening behavior at 20 °C was evaluated after 0, 2, 4, 6, 8, 12, 16 or 20 weeks of storage (−0.5 °C). It was determined that extractable juice content and concentration of titratable acids of ripened fruit decreased with increasing storage. ‘Bosc’ developed the best quality when ripened after 12 weeks of cold storage. However, ‘Comice’ showed the best eating quality after 8–20 weeks of cold storage.

### 1.1. Effect of intermediate temperatures

Exposure of pears to intermediate temperatures (5–10 °C) more quickly stimulates the capability to produce adequate levels of ethylene during ripening at room temperature than exposure of pears to low (−1 to 0 °C) or high (20 °C) temperatures. Mitcham et al. (2000) and Mitcham (unpublished data, Fig. 1) determined that only 7 d of cold storage in air at 0 or 5 °C did not induce ethylene biosynthesis and ripening of ‘Bartlett’ pears after transfer to 20 °C, thereby resulting in rapid and uniform ripening (Table 1). They concluded that storage at 0 °C was considerably less effective for the stimulation of ethylene biosynthesis. Gerasopoulos

### Table 1

Successful protocols for stimulation of ethylene production and pear ripening

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Harvest firmness (N)</th>
<th>Cold storage Days at Temperature (°C)</th>
<th>Ethylene treatment</th>
<th>Days in ethylene</th>
<th>Temperature (°C)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bartlett</td>
<td>75.6–84.5</td>
<td>≥21</td>
<td>−1 to 0</td>
<td>−</td>
<td>0</td>
<td>Mitcham et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>1–2</td>
<td>0</td>
<td>Mitcham et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>100</td>
<td>2</td>
<td>20</td>
<td>Mitcham et al. (2006)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>100</td>
<td>3</td>
<td>5</td>
<td>Mitcham et al. (2006) and Mitcham (unpublished data)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>5 or 10</td>
<td>−</td>
<td>0</td>
<td>Mitcham (unpublished data)</td>
<td></td>
</tr>
<tr>
<td>Bosc</td>
<td>53.4–62.3</td>
<td>3</td>
<td>1 to 0</td>
<td>100</td>
<td>20</td>
<td>Sugar (unpublished data)</td>
</tr>
<tr>
<td></td>
<td>53.4–71.2</td>
<td>14</td>
<td>1 to 0</td>
<td>−</td>
<td>0</td>
<td>Sugar (unpublished data)</td>
</tr>
<tr>
<td></td>
<td>53.4–57.8</td>
<td>&lt;7</td>
<td>−1 to 0</td>
<td>−</td>
<td>0</td>
<td>Chen and Mellenthin (1982)</td>
</tr>
<tr>
<td></td>
<td>57.8–62.3</td>
<td>10</td>
<td>−1 to 0</td>
<td>−</td>
<td>0</td>
<td>Chen and Mellenthin (1982)</td>
</tr>
<tr>
<td>Comice</td>
<td>53.4–57.8</td>
<td>25–31</td>
<td>−1 to 0</td>
<td>100</td>
<td>3</td>
<td>Sfakiotakis and Dilley (1974)</td>
</tr>
<tr>
<td></td>
<td>44.5–48.9</td>
<td>20–25</td>
<td>−1 to 0</td>
<td>100</td>
<td>1</td>
<td>Sugar and Basile (2006)</td>
</tr>
<tr>
<td></td>
<td>48.9–57.8</td>
<td>&lt;17</td>
<td>−1 to 0</td>
<td>100</td>
<td>2</td>
<td>Sugar and Basile (2006)</td>
</tr>
<tr>
<td></td>
<td>48.9–57.8</td>
<td>7–17</td>
<td>−1 to 0</td>
<td>100</td>
<td>3</td>
<td>Sugar and Basile (2006)</td>
</tr>
<tr>
<td></td>
<td>58.7</td>
<td>7</td>
<td>5 or 10</td>
<td>100</td>
<td>20</td>
<td>Sugar and Basile (2006)</td>
</tr>
<tr>
<td>d’Anjou</td>
<td>62.3–66.7</td>
<td>60</td>
<td>−1 to 0</td>
<td>−</td>
<td>0</td>
<td>Klahre et al. (1987)</td>
</tr>
<tr>
<td></td>
<td>57.8–62.3</td>
<td>45</td>
<td>−1 to 0</td>
<td>−</td>
<td>0</td>
<td>Klahre et al. (1987)</td>
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<td></td>
<td>57.8</td>
<td>25–30</td>
<td>−1 to 0</td>
<td>−</td>
<td>0</td>
<td>Klahre et al. (1987)</td>
</tr>
<tr>
<td></td>
<td>57.8–66.7</td>
<td>15–60</td>
<td>−1 to 0</td>
<td>100</td>
<td>7</td>
<td>Chen (2002)</td>
</tr>
<tr>
<td></td>
<td>57.8–66.7</td>
<td>15–60</td>
<td>−1 to 0</td>
<td>100</td>
<td>3</td>
<td>Chen and Mellenthin (1982)</td>
</tr>
<tr>
<td></td>
<td>66.7</td>
<td>&lt;60</td>
<td>−1 to 0</td>
<td>100</td>
<td>3</td>
<td>Chen (1999)</td>
</tr>
<tr>
<td></td>
<td>57.8–66.7</td>
<td>&gt;21</td>
<td>−1 to 0</td>
<td>Normal ripening when fruit was packed in a bag with ethylene-producing ‘Bartlett’ pears</td>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>57.8–66.7</td>
<td>30</td>
<td>−1 to 0</td>
<td>Normal ripening when fruit was packed in a bag with an ethylene capsule</td>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>57.8–66.7</td>
<td>66.7–71.2</td>
<td>40</td>
<td>5 or 10</td>
<td>−</td>
<td>Gerasopoulos and Richardson (1999)</td>
</tr>
<tr>
<td>Colombia Red Anjou</td>
<td>57.8–64.9</td>
<td>60</td>
<td>−1 to 0</td>
<td>−</td>
<td>0</td>
<td>Chen et al. (1997, 1993)</td>
</tr>
<tr>
<td>Red d’Anjou (Gebhard strain)</td>
<td>64.5</td>
<td>0</td>
<td>100</td>
<td>3</td>
<td>20</td>
<td>Chen et al. (1997)</td>
</tr>
</tbody>
</table>

*Ethylene treatment followed by 14 d at −1 °C for a simulated transit period.*
and Richardson (1999) also found that storing ‘d’Anjou’ pears harvested at 67–71 °C at 5 or 10 °C for 40 d induced faster softening and ripening at 20 °C compared with fruits only held at 20 °C (Table 1).

2. Effect of controlled atmosphere storage

Controlled atmosphere (CA) storage is based on the alteration and maintenance of gas composition different from that of air (78% N₂, 21% O₂, and 0.03% CO₂) in the storage atmosphere of the commodity (Kader, 2002a). The concentration of O₂ and CO₂ used in pear storage depends on the cultivar, but generally ranges between 1 and 3% O₂ and 0 and 5% CO₂ (refer to Richardson and Kupferman 1997) and Kupferman (2003) for detailed recommendations by cultivar. In pears, it has been demonstrated that appropriate CA storage increases storage life (Wang and Mellenthin, 1975; Drake and Chen, 2000; Drake and Elfving, 2004), reduces development of yellow color (Knee, 1973; Ma and Chen, 2003) and physiological disorders, such as superficial scald and internal breakdown during cold storage.

Maage and Richardson (1998) found that a CA regime of 2% O₂ at −1 to 0 °C delayed autocatalytic ethylene production and fruit ripening, and increased the postharvest chilling requirement by 2 weeks in ‘Red d’Anjou’ and ‘d’Anjou’ pears. In contrast, this same study also found that ‘Bosc’, ‘Packham’s Triumph’ and ‘Comice’ pears showed no change or a very small increase in the postharvest chilling requirement when fruit were stored in CA instead of air, indicating cultivar differences in this response. However, Blankenship and Richardson (1986) reported that ‘d’Anjou’ pears softened faster at 20 °C after they had been stored in 1 or 3% O₂ for 125 and 153 d, compared to regular air (RA) storage.

Van Eeden et al. (1991) evaluated ethylene production and 1-aminocyclopropane-1-carboxylic acid (ACC) content during and after CA storage (1% O₂ + 1% CO₂ at 0.5 °C for 12–20 weeks) in ‘Beurre Bosc’ pears. They determined that both ACC content and ethylene production rate increased during the storage period as also shown in RA storage (see Section 1). These results indicate that the positive combined effect of chilling temperature and storage time on the stimulation of ethylene biosynthesis is not completely inhibited by CA storage.

Application of coatings made of various materials to pear fruit can modify the internal atmosphere of the fruit during storage and may prolong shelf life, retarding softening and color changes. Amarante et al. (2001) characterized the ripening behavior of ‘Bartlett’, ‘Bosc’, ‘Comice’, and ‘Packham’s Triumph’ pears coated with 0, 5, 10, 20, 40, and 100% of commercial carnauba-based wax solution in relation to fruit internal atmosphere. They suggested that modification of the internal partial pressure of O₂ rather than that of CO₂ was the principal factor that influenced the ripening behavior of coated pears at 20 °C. The effect of the coating on softening, color development and possible hypoxia injury depended on the cultivar and fruit maturity at the time of coating, as well as the storage and ripening temperatures, which suggest that optimization of a coating treatment should consider all these aspects.

Drake (1997) evaluated the effect of wax application on fruit quality. He found that the temperature used for drying the wax applied to pears in the packinghouse affected fruit ripening. Waxing, cold-dried fruit needed more time to ripen than waxed, hot-dried or non-waxed pears. Waxing fruit showed lower CO₂ production, but higher internal concentrations of CO₂ than non-waxed fruit. Fruit waxed after harvest or after 90 d of cold storage took more time to ripen when compared with non-waxed fruit.

The physiological effect of O₂ on pears has been associated with a reduction in Krebs cycle activity, cytosolic pH and ATP/ADP ratio (Nanos et al., 1992, 1994; Nanos and Kader, 1993; Chervin and Truett, 1999). These physiological responses, perhaps associated with anaerobic respiration, are alternative mechanisms for the cell to generate small amounts of energy because the electron transport activity is inhibited by low O₂ concentration (Nanos et al., 1994). However, the physiological effect of CO₂ on respiration has also been related with a reduction in Krebs cycle activity (Ke et al., 1994) and the glycolytic pathway (Kerbel et al., 1988, 1990). With respect to ethylene production, both high CO₂ and low O₂ appear to inhibit the ethylene biosynthetic pathway (Yoshida et al., 1986). The conversion of ACC to ethylene is performed by 1-aminocyclopropane-1-carboxylic acid oxidase (ACO), a member of the dioxygenase family of enzymes that uses molecular oxygen (Fig. 6) and ascorbic acid as co-substrates, and iron as a co-factor in the production of ethylene (Vioque and Castellano, 1998; Castellano and Vioque, 2000). Thus, CA storage effectively controls one of the substrates necessary for catalytic activity of ACO, and the subsequent production of ethylene. In contrast, the role of elevated CO₂ concentrations in the inhibition of ethylene biosynthesis in pear fruit remains unclear. However, de Wild et al. (1999, 2003) suggested that CO₂ might antagonize the ethylene receptor binding protein, and might also act by inhibiting the conversion from ACC to ethylene by ACO.
Table 2

<table>
<thead>
<tr>
<th>Time in ethylene (h)</th>
<th>Proportion of fruit ripe after 5 d at 20°C</th>
<th>Days at 0°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>2001</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2002</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Pear fruit were exposed to 100 μL·L⁻¹ ethylene at 20°C then placed in air at 0°C. Source: Sugar and Basile (2006).

Table 3

<table>
<thead>
<tr>
<th>Harvest</th>
<th>Time in ethylene (h)</th>
<th>Proportion of fruit ripe after 7 d at 20°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>1b</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2b</td>
<td>3</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>72</td>
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<td></td>
<td>12</td>
<td>96</td>
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<tr>
<td></td>
<td>92</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>97</td>
</tr>
</tbody>
</table>

Pears were placed in plastic containers without polyliners and treated with 100–400 μL·L⁻¹ ethylene for 0, 24, 48, 72 or 96 h at 20°C. Fruits were stored for 2, 4, 6, and 8 weeks at -1°C. Adapted from Facteau and Mielke (1998).

3. Effect of ethylene treatment

Treating pears with ethylene after harvest can overcome some or all of the chilling requirement for developing ripening capacity (Tables 2 and 3). This treatment, known as “ethylene conditioning”, generally includes exposure to temperatures near 20°C and an exogenous application of ethylene, which is needed to induce ethylene biosynthesis. However, there is a need for standardization in the use of the term conditioning. While some have used conditioning to describe fruit exposed only to ripening temperatures, we define conditioning as treating fruit with ethylene (“ethylene conditioning”) and/or cold temperatures (“temperature conditioning”) to develop their capacity for ethylene biosynthesis and ripening. Wang et al. (1972a) found that as little as 0.5–2.0 μL·L⁻¹ ethylene applied continuously after harvest for 20 d at 20°C was sufficient to promote ripening capacity in ‘d’Anjou’ pears, depending on fruit maturity. Nevertheless, use of higher concentrations of ethylene (100 μL·L⁻¹) is a normal practice in both research and commercial operations to induce ripening capacity in pears. However, Sharrock and Henzell (unpublished data) showed that treatments that are sufficient to induce full softening of ‘d’Anjou’ pears may not necessarily be sufficient to trigger release of the full aroma potential, particularly early in the season for pears that have not satisfied their chilling requirement (see more details of this study in the section on flavor and aroma). In spite of that, it is generally understood that 100 μL·L⁻¹ ethylene is sufficient to saturate the ethylene response as confirmed by Facteau and Mielke (1998) in ‘d’Anjou’ pears.

Many studies have shown the successful effect of ethylene to trigger ripening capacity in pears. Puig et al. (1996) concluded that ‘Bartlett’ pear fruit grown in Oregon and not exposed to chilling temperatures (−1°C) or stored for less than 3 weeks at chilling temperatures, should be ripened at 20°C with 100 μL·L⁻¹ ethylene for 7 d, while fruit stored for 4 or more weeks at −1°C can be ripened at 20°C without ethylene treatment. Mitcham et al. (2000, 2006) demonstrated that freshly harvested ‘Bartlett’ pears grown in California can be induced to ripen by exposure to 100 μL·L⁻¹ ethylene for 1, 2, or 3 d at 20, 10 or 5°C, respectively, followed by ripen-

Fig. 2. Changes in firmness (N) and color (hue°) of California ‘Bartlett’ pears during ripening at 20°C following ethylene conditioning at 7.5°C (A and D), 10°C (B and E), and 20°C (C and F) for 24, 48, and 72 h. At each temperature, one group of fruit was exposed to air plus 100 μL·L⁻¹ ethylene for 24, 48, and 72 h, and a control group was exposed to air without ethylene at the same temperature and times. Data points represent means of three replicates ± S.E. Mitcham et al. (unpublished data).
ing at warm temperatures. Therefore, fruit temperature during the ethylene treatment influences the degree of induction of ethylene biosynthesis in 'Bartlett' pears, with longer ethylene exposure required at lower temperatures (Fig. 2; Agar et al., 2000a).

Additionally, Chen et al. (1996) demonstrated that 'd’Anjou' fruit harvested at 67 N and stored at −1°C for less than 8 weeks were capable of ripening normally only after a conditioning period of 3 d with 100 μL L⁻¹ ethylene at 20°C, followed by 14 d at −1°C to simulate transit to a distant market. According to these authors, ‘d’Anjou’ fruit stored for more than 8 weeks at −1°C could be ripened without ethylene (Fig. 3); however, improvements in sensory quality were noted in fruit stored 8 weeks and conditioned with ethylene during ripening over fruit not given the ethylene treatment after storage (Chen et al., 1996, Fig. 3).

Chen (2002) also studied the optimum temperature during ethylene treatment of ‘d’Anjou’ pears harvested at 62.3 ± 4.4 N during the first 8 weeks of storage. Fruit were held in cold storage at −1°C for 2, 4, 6 or 8 weeks and then conditioned at 7, 13, or 16°C with 100 μL L⁻¹ ethylene for 3 or 7 d to simulate short and long distance shipment to market. The author’s goal was to achieve pears with 40 N firmness on day 1 of ripening at 20°C, and no more than 27 N on day 5 of ripening. A temperature of 7°C during ethylene treatment showed the best potential for a long distance shipment (7 d) while a temperature of 16°C was the best for a short distance shipment (3 d) during the first 8 weeks after harvest (Table 1).

Ripening capacity can also be induced using ethylene-releasing capsules within the packaging materials (Chen, 2000; Ma et al., 2000, Table 1). Recently, Sharrock and Henzell (unpublished data) found that prototype ethylene-release capsules developed by HortResearch, New Zealand, can maintain minimum ethylene levels of 65 μL L⁻¹ for at least 7 d in pears packed in boxes with standard liners. They suggest that these capsules can facilitate pear conditioning during transport in refrigerated trucks and allow delivery of pears capable of ripening and developing appropriate texture, aroma and flavor attributes.

Ethylene treatment protocols that effectively substitute for the chilling requirement have also been developed for the following cultivars: ‘Columbia Red Anjou’ and ‘Red d’Anjou’ (Gebhard strain) (Chen et al., 1994, 1997), ‘Comice’ (Sugar and Basile, 2006), ‘Bosc’ (Chen and Mellenthin, 1982; Sfakiotakis and Dilley, 1974), and ‘Forelle’ (du Toit et al., 2001). Table 1 presents a summary of the main protocols that have been shown to induce appropriate softening and ripening capacity in pears. Whether all the protocols presented in Table 1 would also be the best protocols to maximize flavor and aroma in pears requires further investigation.

3.1. Ripeness indicators

External color change in some winter pears is not a good ripening indicator because yellow color may be obtained before ripening and softening, especially when pears have received previous long-term cold storage. Furthermore, some pear cultivars do not change skin color during ripening. Scientists from HortResearch developed clamshells with ripeness sensing labels (RipeSense®) that can be used to report the ripeness status of pears by changing color as aroma volatiles increase in the package atmosphere (Sharrock, 2005; White, 2005). Klein et al. (2006) also patented a non-invasive colorimetric ripeness indicator that detects ethylene levels produced by the fruit. It is composed of an ethylene permeable substrate that has a colorimetric reagent in a sticker that adheres to the fruit surface and changes color according to the ethylene concentration in the environment.

3.2. Flavor and aroma

Pear aroma can be influenced by a broad range of factors, including genetic differences, preharvest factors, maturity at harvest, storage conditions, and fruit physiology (intra-fruit volatile localization, ripening, senescence and presence of disorders) (Rapparini and Predieri, 2003). Sharrock and Henzell (unpublished data) using RipeSense® labels found that ethylene concentrations greater than 10 μL L⁻¹ appeared to have a positive impact on aroma production during ripening at 20°C when ‘d’Anjou’ fruit stored 1, 3 or 4.5 weeks at −1°C were treated with ethylene (0, 0.5, 2, 10, 30, and 100 μL L⁻¹) for 3 or 7 d at 20 or 7°C. They proposed that the ethylene threshold required for stimulation of aroma production in pears might be higher than that required for softening induction (0.5–2 μL L⁻¹ in ‘d’Anjou’ pear as described by Wang et al., 1972a). Their results also suggest that continuous exogenous ethylene treatment might provide flavor benefits over short-term exposures to ethylene.

4. Cultivar differences

Pear cultivars vary in their requirement for a postharvest ethylene or chilling treatment to ripen satisfactorily (Table 1). However, little information has been published comparing the ripening characteristics of cultivars stored under the same conditions. Chen et al. (1993) studied the ripening behavior of ‘Columbia Red Anjou’ and ‘Red d’Anjou’ (Gebhard Strain) pears after cold storage. They found that even though these cultivars were harvested at a similar maturity, they displayed different ripening behavior after monthly
removals from storage at −1 °C. ‘Red d’Anjou’ fruit required a longer chilling period than ‘Columbia’ fruit to produce measurable rates of ethylene (Fig. 4). However, ACC content in unripe fruit after cold storage of both strains was similar at each corresponding storage interval. During ripening, ACC content in ‘Columbia’ fruit increased twofold to threefold, while that in ‘Red d’Anjou’ fruit changed little, suggesting lower ACS activity. ‘Columbia’ fruit ripened normally after 3 months of cold storage, and developed a buttery and juicy texture. ‘Red d’Anjou’ fruit also softened after 3 months of cold storage, but to a lesser extent than ‘Columbia’ fruit and the textural quality was inferior.

5. Preharvest temperature, growing region and harvest maturity effects

Temperature during fruit development also plays an important role in ripening behavior. Premature ripening of ‘Bartlett’ pears on the tree has been reported in Oregon, Washington and California when abnormally cool temperatures occurred during the 4–5 weeks prior to harvest (Wang et al., 1971). This premature ripening was related to an increase in abscisic acid (ABA) concentration during the preharvest period (Wang et al., 1972b).

Mellenthin and Wang (1976) found that ‘d’Anjou’ fruit quality and the capacity to ripen after long storage periods were associated with the daily-hourly average (DHA) temperatures prevailing during the 6 weeks before harvest. Fruit grown at 17.2 and 13.9 °C DHA presented higher acid and sugar contents while fruits from 20.0 and 11.7 °C DHA temperature failed to ripen properly and had lower quality. Failure to ripen after long cold storage was related to high protein levels in the fruits (Mellenthin and Wang, 1976). Fruit exposed to lower DHA temperatures had a greater susceptibility to friction discoloration, while fruit harvested with higher DHA temperatures presented higher incidence of superficial scald. Temperatures during this period did not appear to affect fruit harvest maturity, size or soluble pectin content.

Agar et al. (1999) concluded that ‘Bartlett’ pears from growing locations with cooler preharvest temperatures and/or from later harvests within a growing location had higher ethylene production rates during ripening without postharvest ethylene or chilling treatments, indicating a difference in their ability to ripen. For this reason, differences in ripening behavior and response to ripening inhibitors might occur in fruits of the same cultivar grown in different environments.

Facteau and Mielke (1998) studied the effect of harvest maturity and a postharvest pre-storage ethylene treatment on ‘d’Anjou’ pears. They determined that the rate of fruit softening was a function of hours of ethylene treatment, length of storage, days of ripening, and harvest maturity (60–68 N). While a 72 h ethylene treatment was sufficient for fruit harvested at 68 N to adequately soften after 6 weeks of storage at −1 °C and 7 d at 20 °C, pears harvested at 60 N ripened normally after 72 h of ethylene exposure and only 2 weeks of storage (Table 2). However, they also mentioned that fruit exposed to ethylene for 96 h had a higher percentage of fruit that ripened to acceptable eating quality and some benefits might be obtained with this longer duration of ethylene exposure, especially for those fruit cold stored for only 2–4 weeks and harvested early (68 N). These results illustrate the enormous effect of maturity on pear ripening.

Chen et al. (1994, 1997) studied the ripening behavior of ‘Red d’Anjou’ (Gebhard strain) pears after cold storage as influenced by harvest maturity and ethylene treatment. They determined that fruit harvested at different firmness levels presented distinct ripening behaviors after storage in air at −1 °C. Fruit stored for 3 months did not develop the capacity to ripen normally during a period of 8 d at 20 °C if they were harvested with firmness levels between 53 and 62 N. Fruit harvested at less than 53 N showed some ripening activity after 1 month of storage. Additionally, Chen et al. (1997) found that ‘Red d’Anjou’ pears harvested at approximately 64 N could be ripened to good texture and flavor by treating the fruit with 100 μL L−1 of ethylene at 20 °C for 3 d, followed by 14 d of simulated transit at −1 °C, before ripening at 20 °C for market (Table 1).

Chen and Mellenthin (1981) tested the effects of harvest date on ripening capacity and postharvest life of ‘d’Anjou’ pears. They concluded that dessert quality [texture, juiciness, and flavor quality
as determined by the authors (refer to Mellenthin et al., 1980 for complete description) of late-harvested fruit (firmness 53–58 N) ripened without ethylene exposure decreased after 90 d of storage while quality of optimally harvested fruit (60–63 N) continued to improve until 150 d in storage (Fig. 5). They also determined that concentrations of titratable acids and soluble solids differed among harvest groups. Fig. 5 shows the effect of maturity on ripe fruit quality and clearly indicates that fruit harvested later in the season obtained higher quality values after shorter storage times than early harvested fruit. This pattern is likely associated with the fact that later harvested fruit require a shorter chilling period to fully induce their ripening capacity (see also Table 1).

The effect of fruit maturity at harvest on the chilling requirement and dessert quality of ‘Bosc’ pears was investigated by Chen and Mellenthin (1982). They found that when fruit were harvested between 53 and 58 N, they required less than 7 d of chilling at −1 °C to develop the capacity for ripening while fruit harvested with 58–63 N were able to ripen after 10 d of chilling (Table 1). They also determined that the dessert quality of ‘Bosc’ pears was independent of fruit maturity within the appropriate maturity range and began to decline after 60 d of storage.

6. Molecular and enzymatic approaches to characterize pear ripening

In recent years, researchers have characterized ethylene biosynthesis during pear ripening under different conditions (normal ripening, 1-MCP treatment, high CO2 atmospheres), evaluating the behavior of 1-aminocyclopropane-1-carboxylic acid, ACC synthase (ACS), and ACC oxidase (Fig. 6). In addition, developments in molecular biology have permitted detection of genes associated with ethylene synthesis and action that aid in our understanding of the physiological changes associated with pear ripening.

6.1. Ethylene synthesis

Fig. 6 summarizes the main compounds and enzymes associated with ethylene biosynthesis during fruit ripening. Briefly, the amino acid methionine is converted into S-adenosyl-methionine (SAM). Subsequently, SAM is converted by ACS into ACC which is then oxidized by ACO to ethylene.

Fonseca et al. (2005) studied ACO activity during pear (cv. ‘Rocha’) ripening at 23 °C, and after three different conditions: treatment with 100 μL·L⁻¹ ethylene for 24 h after harvest, no ethylene treatment after harvest, and cold storage for 60 d at 0 °C. They concluded that ACO activity during ripening was significantly higher in fruit stored at low temperatures for 60 d than fruit ripened immediately after harvest. They also found that ethylene-treated fruit had higher ACO activity than non-ethylene-treated fruit, but not as high as cold stored fruit. Agar et al. (2000b) compared ACO and ACS activity in ‘Bartlett’ pears stored 0, 2, 4, 6, and 12 weeks at −1 °C and subsequently ripened at 20 °C. They obtained the highest activity for both enzymes in fruit stored for 12 weeks, with little activity between 0 and 6 weeks of cold storage. However, once ripening was induced either by ethylene (100 μL·L⁻¹) or by exposure to chilling temperatures, both enzyme activities tended to increase during ripening. Prior chilling exposure appeared to stimulate ACS and ACO activity during ripening; the longer the chilling period the higher the enzyme activity during subsequent ripening. Increasing ACO activity and ACC content during storage of ‘d’Anjou’ fruit (≈90 d) at −1 °C was also reported by Gerasopoulos and Richardson (1997b).

Chen et al. (1997) studied the promotion of ripening in ‘Red d’Anjou’ (Gebhard strain) pears by treatment with ethylene. They determined that ethylene treatment at harvest with 100 μL·L⁻¹ for 3 d followed by 14 d at −1 °C induced normal ripening at 20 °C while fruit not treated with ethylene did not ripen normally even when pears had been previously stored for 4 months at −1 °C. The ethylene treatment induced an increase in ACS activity and conversion of ACC to ethylene. Tissue conversion of ACC to ethylene was also induced by storing fruit at −1 °C for 2 months or longer; however, ACS activity in chilled fruit remained very similar to the activity at harvest. The authors suggested that the promotion of normal ripening in this cultivar by ethylene treatment might be attributed to the induction of ACC to ethylene conversion and ACS activity, followed by increasing ACS activity at 20 °C.

When ‘Rocha’ pear fruit were harvested and held in air at 23 °C for 24 d to ripen, the activity of ACO-related gene expression increased by day 15 and remained elevated until day 24 when the fruit were senescent (Fonseca et al., 2004). The authors proposed that this gene’s action (associated with ripening, senescence and defense signaling processes) may be associated with the main changes in global gene expression during ripening, including energy production and transfer, development of color and aroma, cell wall modification, and fruit softening. Lelièvre et al. (1997) found that ACS gene expression in ‘Passe Crassane’ (Pc) pears was regulated by ethylene only during or after a chilling treatment, while ACO gene expression could be induced separately by either chilling or ethylene. El-Sharkawy et al. (2004) studied ACS gene expression also in Pc pears, which require long chilling treatments before normal ripening, ‘Old-Home’ (OH) pears that do not require a chilling treatment and OH × Pc hybrids. They found that four of seven Pc-ACS cDNAs isolated had different behaviors associated with the cold requirement. In cold dependant cultivars, Pc-ACS1α transcript accumulated during the cold treatment and Pc-ACS2α during ripening. In contrast, Pc-ACS1b and Pc-ACS2b were found only during ripening of cold-independent cultivars. Pc-ACS3, 4 and 5 transcripts were similarly associated in all genotypes. Using these types of results, characterization of ripening differences among cultivars is possible.

Pech et al. (2002) characterized and studied four members of the ACS family during cold storage and ripening of ‘Passe Crassane’ pears (Fig. 7). They determined that these genes were differentially expressed in the presence or absence of chilling treatment (80 d at 0 °C). The expression of the ACS1 transcript was highly regulated by cold storage while ACS3 was expressed mainly after harvest and in the absence of a chilling treatment (80 d at 20 °C). ACS4 and ACS5 were essentially associated with the climacteric peak of ethylene production.
Satoh et al. (2000) evaluated ethylene synthesis in three different pear cultivars: ‘La France’ and two strains (P12-9 and P12-111) derived from a cross between ‘La France’ and ‘Le Lectier’ that do not respond to cold-induced ripening. ACS activity and ACC content increased in response to the cold treatment in P12-9 fruit. Although this strain produced ethylene, endogenous or exogenous ethylene did not induce softening, suggesting that ethylene was not perceived. P12-111 fruit also produced some ethylene, but neither ethylene production nor softening was induced by cold storage. This pattern indicates that P12-111 fruit have a reduced ability to perceive the cold stimuli and/or to respond to ethylene.

6.2. Ethylene action

The majority of studies on ethylene perception mechanisms have been performed on Arabidopsis thaliana and tomato. The ethylene binding proteins function as negative regulators of ethylene response, i.e., ethylene binding inactivates them (Guo and Ecker, 2004; Kevany et al., 2007). El-Sharkawy et al. (2003) isolated and characterized four mRNA transcripts associated with these receptors in ‘Passe-Crassane’ pears. They found that Pc-ETR1A expression increased during cold storage while Pc-ETR1A, Pc-ERS1A, Pc-ETRS, and Pc-CTR1 (constitutive triple response 1) expression increased during fruit ripening and after ethylene treatment. Fruit treated with 1-MCP, an ethylene action inhibitor, did not display a similar increase in mRNA transcript abundance of these genes, even after cold storage and ripening at 20 °C.

7. Effect of storage time and temperature on ripening rate and quality

The number of days required for pear fruit to fully soften and develop full flavor and buttery texture varies depending on cultivar, duration of low temperature storage before ripening, atmosphere composition during storage, and pear fruit temperature during ripening. Unfortunately, little published information is available on the rate of ripening for cultivars other than ‘Bartlett’ and ‘d’Anjou’. Table 4 presents the effect of storage time on ripening rates for these two cultivars. The longer the time in cold storage, the faster the rate of ripening. Agar et al. (2000b) found that ‘Bartlett’ fruit exhibited higher ethylene production and faster ripening upon transfer to 20 °C when the length of cold storage at −1 °C was increased. On the other hand, CA storage (1.5% O₂ and 0.5% CO₂) generally delays the effect of cold storage on subsequent ripening rates in California ‘Bartlett’ pears (even in fruit stored for 6 months) to almost the same rate as obtained in pears ripened immediately after harvest using an exogenous ethylene treatment (Mitcham, unpublished data). The fruit temperature during ripening also affects ripening rates (Fig. 8). Raising the temperature from 15 to 25 °C increases in mRNA transcript abundance of these genes, even after cold storage and ripening at 20 °C.

8. Cooling and warming of fruit for ripening

Because of the great effect of fruit temperature on the fruit’s response to ethylene and the rate of ripening, maintaining narrow...
9. Treatments to inhibit ripening

9.1. 1-Methylcyclopropane (1-MCP)

1-MCP is an ethylene action inhibitor (Sisler and Blankenship, 1996; Sisler and Serek, 2003) and has been evaluated for its ability to extend the storage life of pears and delay ripening (Fig. 6). It has been broadly demonstrated that postharvest application of 1-MCP decreases softening, internal browning, color development, storage scald, respiration rate, ethylene production, and ACS and ACO activity in pear fruit (Baritelle et al., 2001; Argenta et al., 2003; Kudo et al., 2003; Hiwasa et al., 2003; Calvo and Sozzi, 2004; Calvo, 2004; Ekman et al., 2004; Trinchero et al., 2004; Mwaniki et al., 2005).

However, it is still not clear what is the best combination of harvest maturity, 1-MCP concentration, application conditions (temperature, time), and storage time after 1-MCP treatment to adequately control fruit softening and development of physiological disorders, while simultaneously allowing the fruit to ripen to good quality for marketing. Most of the research thus far has focused on altering the 1-MCP treatment concentration.

Ekman et al. (2004) studied the effect of 1-MCP concentrations applied at 0 °C for 12 h on ‘Bartlett’ pears. In one test, fruit treated with 0.01, 0.1, and 0.5 μL·L⁻¹ softened during ripening at 20 °C similarly to untreated fruit after 0, 6 and 18 weeks in cold storage (−1 °C), respectively. Fruit treated with 10.0 μL·L⁻¹ did not soften after 24 weeks at −1 °C and more than 14 d at 20 °C. Although 1-MCP treated fruit had less internal browning and superficial and senescent scald incidence than untreated fruit, these physiological disorders affected fruits from all treatments that ripened after 18 weeks at −1 °C and subsequent ripening. Concentrations between 0.1 and 0.5 μL·L⁻¹ 1-MCP appeared to have potential to extend storage life while allowing fruit to eventually ripen.

Calvo (2004) tested the effect of 1-MCP applied at 8 °C for 24 h on ‘Williams’ (‘Bartlett’) pears at two different harvest maturities (81 and 69 N). For the optimum harvest maturity (81 N), fruit treated with 0.2 μL·L⁻¹ developed adequate edible firmness after 150 d RA storage plus 8–9 d at 20 °C, but the fruit had some incidence of internal browning. For fruit from the late harvest (69 N), 1-MCP concentrations between 0.4 and 0.5 μL·L⁻¹ provided the same effect as fruit harvested at optimal maturity and treated with 0.2 μL·L⁻¹. However, fruit was also affected by internal browning, but to a lesser extent than untreated fruit.

The physiological state of the fruit at the time of 1-MCP treatment has a crucial influence on the effect of 1-MCP. Mitcham et al. (unpublished data) found that 1-MCP was ineffective when it was applied to ‘Bartlett’ pears harvested at 58 N. When ‘Bartlett’ pears were harvested at 68 N and stored for 1 or 2 weeks at −1 °C prior to treatment with 1 μL·L⁻¹ 1-MCP, fruit ripening was still significantly inhibited (Mitcham et al. unpublished). Veltman et al. (unpublished data) also studied the effect of 1 and 50 μL·L⁻¹ 1-MCP applied to ‘Bartlett’ pears that had been stored at 0 °C for 6 weeks (firmness at treatment = 82 N). During ripening at 20 °C, CO₂ and ethylene production were significantly reduced by treatment with 1 μL·L⁻¹ 1-MCP, but there was no effect on fruit firmness or skin color. Interestingly, treatment with 50 μL·L⁻¹ 1-MCP had no effect on fruit softening, color or ethylene production, and even stimulated fruit respiration. This variability in response to 1-MCP by stored ‘Bartlett’ pears requires further investigation.

Argenta et al. (2003) tested the effects of 0.01, 0.10 and 1 μL·L⁻¹ 1-MCP applied for 12 h at 20 °C to freshly harvested ‘d’Anjou’ pears (≈68 N maturity). Concentrations as low as 0.01 μL·L⁻¹ 1-MCP decreased ripening rates after up to 4 months of storage at 1 °C and 7 d ripening at 20 °C. Higher concentrations delayed ripening for even longer storage periods, however; fruits eventually softened at firmness values below 27 N after 6 or 8 m in cold storage.

Table 5

<table>
<thead>
<tr>
<th>Days required to reach the one-half cooling temperature (T_{1/2})</th>
<th>Pallet levels</th>
<th>Place-packed</th>
<th>Tray-packed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outside fruit</td>
<td>Inside fruit</td>
<td>Outside fruit</td>
</tr>
<tr>
<td>1 bottom</td>
<td>2.1</td>
<td>3.3</td>
<td>1.8</td>
</tr>
<tr>
<td>2</td>
<td>4.9</td>
<td>8.7</td>
<td>3.4</td>
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<tr>
<td>3</td>
<td>4.9</td>
<td>12.4</td>
<td>4.3</td>
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<tr>
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<td>15.0</td>
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<td>6</td>
<td>7.0</td>
<td>13.0</td>
<td>4.1</td>
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<tr>
<td>7 top</td>
<td>2.0</td>
<td>4.9</td>
<td>1.7</td>
</tr>
</tbody>
</table>


a Air flow in cold room 0.20 m·s⁻¹ around the pallet surface. T_{1/2} (fruit starting temperature:fruit storage temperature = 0.5 °C storage room temperature).

b Start temperature = 19.6 °C, room temperature = 0.1 °C, and T_{1/2} = 9.9 °C.

c Start temperature = 21.6 °C, room temperature = 0.3 °C, and T_{1/2} = 10.9 °C.
and subsequent ripening during 7 d at 20 °C. Ethylene applied to 1-MCP-treated fruit after storage did not consistently reduce the 1-MCP effect. Superficial scald, core browning, and decay development were less severe in 1-MCP-treated fruit.

Bai and Chen (2005) studied the effect of 1-MCP applied to 'd'Anjou' pears after cold storage. Fruit were stored 2 or 4 months in RA or 8 months in CA (2% O₂ + 1% CO₂). After each storage period, fruit were treated with 100 μL·L⁻¹ of ethylene applied at 20 °C for 0, 1, 2, 3 or 4 d. Fruit were subsequently treated with 1 μL·L⁻¹ of 1-MCP for 24 h at 20 °C, and held at 20 °C for ripening. Flesh firmness scores for the fruit were 61.4, 56.5, and 56.5 N after 2 and 4 months in RA and 8 months in CA storage, respectively. They concluded that with 2 d (for 2 and 4 months storage in RA) or 1 d (for 8 months storage in CA) of ethylene application before 1-MCP treatment, the time at 20 °C before the fruit were fully softened was extended to 14 d while non-treated fruit were fully soft after 7–9 d.

Ekman et al. (2004) studied 'Bartlett' pears harvested at 84 N firmness and treated with 0.2, 0.4 μL·L⁻¹ and 1-MCP at 0 °C for 12 h. One-half of the fruit was treated during 4 or 6 weeks at −1 °C and then stored for an additional 4 or 6 weeks. Fruit ripened after 4 weeks had a reduced rate of color change and softening during ripening compared with fruit from the initial 1-MCP application or fruit ripened after 6 weeks. Mattheis et al. (2000) found that reapplication of 1-MCP prolonged the effect compared with fruit only treated at harvest. The reapplication was most effective when ethylene production was <0.1 μL·L⁻¹. These results suggest that the effect of 1-MCP can be stronger if reapplications are made at the appropriate time during cold storage.

Rizzolo et al. (2005) tested the effect of 1-MCP (0.025 and 0.05 μL·L⁻¹) applied at −0.5 °C for 24 h on 'Conference' pears. Fruit were stored in RA or CA, treated with 1-MCP after 7 and 14 weeks, and evaluated after ripening following storage for 7, 14 or 22 weeks. Fruit treated with 0.05 μL·L⁻¹ 1-MCP had lower ethylene production and higher firmness than fruit treated with 0.025 μL·L⁻¹. Re-treatments with 1-MCP had little effect on ripening. Scald incidence was not prevented with the 1-MCP application, but it helped to decrease the severity of the symptoms. The best sensory quality was obtained after 14 or 22 weeks in RA storage after treatment with either level of 1-MCP, by maintaining a fresh flavor while untreated fruit became watery or grainy. In this study, CA enhanced the effects of 1-MCP.

Eccher Zerbini et al. (2005) tested the effect of 1-MCP (0.025 and 0.05 μL·L⁻¹) applied every 2 months for 24 h at −0.5 °C on 'Conference' and 'Abbé Fétel' pears stored in RA and CA (2% O₂ + 0.7% CO₂). They determined that 'Abbé Fétel' was much less sensitive to 1-MCP than 'Conference' and CA storage maintained the 1-MCP effect longer than RA storage. When 0.025 μL·L⁻¹ 1-MCP was applied, the softening of 'Conference' pears was similar to untreated fruit after only 34 d of storage at −0.5 °C (both in RA and CA). However, when fruit were treated with 0.05 μL·L⁻¹ 1-MCP, softening was similar to untreated fruit after 83 d of storage in RA and 162 d of CA storage. Repetition of the 1-MCP treatment during cold storage was not effective.

Bai et al. (2006) treated 'Bartlett' pears (80 N at harvest) with 1-MCP (0.3 μL·L⁻¹, 24 h, 20 °C) and stored them at −1 °C in RA or CA for 2–9 months. After storage, the fruit were held at 10°, 15° or 20° C in a factorial-designed experiment with durations of 5, 10 or 20 d. 'Bartlett' pears recovered the ability to ripen, as determined by firmness values lower than 27 N after ripening at 20 °C, when fruit were stored in RA for more than 2 months and held 10 or 20 d at 10°, 15° or 20° C. However, ripening at 20 °C alone appeared to be more effective than intermediate temperatures to induce softening in 1-MCP treated fruit. Bai et al. (2006) also found that 'd'Anjou' pears (64 N at harvest) were more sensitive to 1-MCP than 'Bartlett' pears. A lower concentration (0.05 μL·L⁻¹) decreased scald incidence in storage, while allowing 'd'Anjou' fruit to soften to less than 27 N after 4 m in storage at −1 °C and approximately 20 d ripening at 20 °C.

DeEll and Murr (unpublished data) treated 'Bosc' pears (harvested at 64 N and cooled for 3 d at 0 °C before 1-MCP treatment) with 0.3 μL·L⁻¹ 1-MCP during 24 h at 0 °C. They found that after 2.5 and 4.5 months of storage, keeping the fruit at 10 °C for 5 d had no significant effect on fruit ripening and overall quality. In general, 1-MCP treated fruit had higher firmness than untreated fruit, but treated fruit softened to approximately 23–27 N after 4.5 m in cold storage and 5–10 d of ripening at 22 °C. Delaying pear ripening and senescence to extend fruit storage and marketing periods without the appearance of physiological disorders is the most important potential benefit of 1-MCP application to pears after harvest. The majority of the studies described have shown that 1-MCP is effective when applied at temperatures between 0 and 20 °C. However, the crucial influence of cultivar, maturity at harvest, 1-MCP concentration applied, and storage time after 1-MCP treatment on the potential benefits of the application have been demonstrated. If the optimum combination of these factors for 1-MCP treatment can be reliably determined, this treatment may become a useful tool.

9.2. Ethylene scrubbing

Ripening processes are undesirable during cold storage of pears. Bower et al. (2003) evaluated the effect of ethylene in the storage environment on the quality of 'Bartlett' pears. Fruit from three harvest dates (firmness = 83, 76 and 71 N) were stored for 3 months in 0, 1, 5 or 10 μL·L⁻¹ ethylene at −1 °C and 2 °C. They determined that even 1 μL·L⁻¹ ethylene increased the incidence of physiological disorders, but the ethylene effect was minor compared with the influence of storage temperature. 'Bartlett' fruit stored at −1 °C remained firm, green, and ripened normally upon transfer to 20 °C regardless of the ethylene concentration during cold storage, while fruit stored at 2 °C softened, yellowed, and developed symptoms of superficial scald and internal browning during storage. They concluded that greater benefit could be gained by storing pears at lower temperatures than by scrubbing ethylene during storage. Testoni et al. (2002), Sugar (2002), Retamales et al. (1998) and Truter and Combrink (1993) also found little effect in reducing ripening in cold storage in 'Conference' and 'Packham’s Triumph' pears by scrubbing ethylene from the storage atmosphere.

9.3. Aminoethoxyvinylglycine (AVG)

Aminoethoxyvinylglycine (AVG) inhibits the synthesis of ACS (Ness and Romani, 1980; Romani et al., 1983; Mitcham et al., 1998; Clayton et al., 2000) as shown in Fig. 6. Mitcham et al. (1998) studied the effect of ReTain®, a commercial formulation of AVG, applied to 'Bartlett' pears in the field 3, 2 and 1 week before harvest (125 g active ingredient ha⁻¹, 250L ha⁻¹). ReTain® treatment decreased premature ripening and delayed pear maturity, maintaining higher fruit firmness, greener skin color, and greater starch content at harvest compared with untreated fruit. Application at 1 or 2 weeks prior to the initiation of commercial harvest was the most effective treatment timing. It also had an effect on the rate of ripening when fruit were ripened immediately after harvest; treated-fruit had one-half the ethylene production of untreated pears and firmness after 5 d of ripening was 13 N higher than untreated fruit. However, when fruits were ripened with ethylene gas, differences in firmness between treated and untreated fruit after 5 d ripening were marginal. After 4 months storage at −1 °C, treated fruit firm-
ness and ripening behavior were similar to untreated fruit. Dussi et al. (2000) also found delayed maturity, but little or no effect after 100 d of storage at 0 °C with 'Williams' pears treated in the field 2 weeks before harvest with Retain® at 180 and 125 mg L⁻¹ a.i.

9.4. Mannose

Watkins and Frenkel (1987) indicated that mannose could inhibit many metabolic processes in plant tissues including growth, respiration, ion uptake, and photosynthesis. They determined that softening of pear fruit and the increase in ethylene production and respiration associated with ripening were delayed by a mannose treatment; however, glucosamine and 2-deoxyglucose, analogs of mannose, did not show the same effect. They concluded that the effect of mannose on pear ripening was associated with respiration. The application of mannose resulted in cytotoxic accumulation of mannose 6-phosphate and depletion of inorganic phosphate.

9.5. Calcium

Xuan et al. (2005) determined that an application of boron with calcium affected respiration and ATP/ADP ratio in 'Conference' pears during CA storage. Lara and Vendrell (1998), Raese (1999), Richardson and Gerasopoulos (1993) and Richardson and Al-Ani (1982) associated delays in ripening with concentrations of calcium in cultivars such as 'Passe-Crassane' and 'd'Anjou'. High calcium concentrations in the fruit resulted in a reduction in respiration rate and ethylene evolution during ripening. Firmness in calcium-treated 'Bosc' (Sugar et al., 1994) and 'd'Anjou' (Gerasopoulos and Richardson, 1997c) fruit was higher than in untreated fruit at harvest. Richardson and Gerasopoulos (1993) and Gerasopoulos and Richardson (1997c) suggested that fruit calcium concentration increases the chilling requirement for induction of ripening capacity.

9.6. Miscellaneous ripening inhibitors

Other ripening inhibitors reported in pears include rhizobitoxine, a metabolic product secreted by bacterium Rhizobium japonicum (Wang and Mellenthin, 1977), salicylhydroxamic acid, alpha, alpha-dipyridil, and silver ions (Janes and Frenkel, 1978). Sozzi et al. (2003) determined that concentrations of 10 μL L⁻¹ of nitric oxide (NO) applied at 20 °C for 2 h delayed ethylene production in preclimacteric 'Bartlett' pears.

10. Effect of plant growth regulators

Kondo and Seto (2004) studied changes in jasmonic acid (JA) during ripening in 'La France' pear fruit and interactions between jasmonic acid and abscisic acid. They determined that at the preclimacteric stage, a treatment with JA or JA plus AVG decreased endogenous ABA biosynthesis. They suggested that JA influences ABA synthesis separately from ethylene. At the climacteric stage, ABA treatment increased endogenous JA concentrations and decreased JA when combined with AVG, which suggests that ABA may influence endogenous JA synthesis via ethylene.

Kondo and Takano (2000) studied the effect of the synthetic auxin, 2,4-dichlorophenoxy-propionic acid (2,4-DP) on ripening of 'La France' pears without cold storage conditioning. They applied a solution of 2,4-DP (90 μL L⁻¹) at 143, 151, and 159 d after full bloom (DAFB) to whole trees and compared the fruit with non-treated fruit harvested at 165 DAFB. They determined that ethylene production increased and firmness decreased in 2,4-DP treated fruit, and suggested that this product can be used as an effective method of producing good quality fruit ripened on the tree or replace temperature or ethylene conditioning to induce ripening capacity. Similar results were obtained by Kondo et al. (1999).

Kondo et al. (2006) studied the effect of 2,4-DP (applied at 130 DAFB, 90 μL L⁻¹) on ACS and ACO gene expression in 'La France' pear. ACS and ACO transcript accumulation was not observed in non-stored, non-treated fruit. In 2,4-DP-treated 'La France' fruit sampled at 180 and 190 DAFB, ACS4 mRNA transcript increased considerably while ACS7, ACS3, and ACO1 mRNA levels were similar between 2,4-DP-treated fruit and stored (20 °C, 90% RH for 20 and 30 d) non-treated fruit. These results suggest that ACS4 may be an ACS gene induced by auxin in pears. This might also explain fruit softening that is often observed after applications of naphthyleanecetic acid (NAA), a synthetic auxin, applied preharvest to reduce fruit drop in California grown 'Bartlett' pears (Clayton et al., 2000).

Puschmann and Romani (1983) demonstrated in vitro that 'Passe Crassane' pear cells produce large quantities of ethylene in response to auxin (indoleacetic acid [IAA], NAA, and 2,4-dichlorophenoxy-acetic acid [2,4-D]), CuCl₂, and ACC. Frenkel and Dyck (1973) studied the effect of IAA and 2,4-D on the ripening of 'Bartlett' pear fruits at concentrations of 0.01, 0.1, and 1.0 mM. They found that softening and degreening were inhibited increasingly in response to increased concentrations of IAA. This effect was amplified by 2,4-D at concentrations comparable to those of IAA. These auxins also prevented the climacteric rise in respiration, but stimulated ethylene production. Even though ethylene production was stimulated, the inhibitory effect of auxin on softening was predominant.

Wang et al. (1971) found that applications of gibberellic acid (GA₃) or succinic acid-2,2-dimethyl hydrazide (SADH; Alar) mitigated the effect of prevailing cool temperatures and retarded the incidence of premature ripening in pear. Looney (1972) found that early summer treatments with 750 and 7500 μL L⁻¹ SADH delayed ripening of 'Bartlett' pears, but this effect was counteracted by both delayed harvest and postharvest storage at 4.4 °C. Ben-Arie and Ferguson (1991) determined that GA₃ did not interfere with cell respiration rates in 'Passe Crassane' pear cell suspensions, but it did affect ethylene production. However, the degree of inhibition decreased as the cell cultures aged. They suggested that the site of ethylene inhibition by GA₃ appeared to be related with ACO.

11. Conclusions

European pears do not generally have the capacity to ripen at harvest, but must be subjected to cold temperatures or treated with ethylene to induce their capacity for ripening. Cold storage has been shown to promote ethylene biosynthesis, but the response varies depending on several factors including cultivar, maturity at harvest, length of cold storage, temperature in storage, and gas composition in the storage atmosphere. Further research is needed, particularly in cultivars other than 'Bartlett' and 'd'Anjou', to determine the requirements for full induction of ripening capacity and the effect of previous cold storage, ethylene conditioning, and fruit temperature on the rate of ripening and final fruit sensory quality. Our ability to investigate induction of genes related to ethylene biosynthesis and perception and its relationship with cold temperatures in pear fruit will allow rapid comparisons of cultivars, strains and the effect of harvest maturity and handling practices on the ripening capacity of pear fruit.

A number of methods are available and others are under development to slow development of pear maturity and ripening on the tree and ripening and senescence of fruit after harvest and during storage, including 1-MCP and AVG. In addition to appropriate temperature and relative humidity control during storage, careful fruit
handling, and sanitation practices, CA storage remains one of the best options to control ripening and senescence during long-term cold storage of pears, maintaining high quality for much longer than RA-stored fruit and controlling physiological disorders such as scald and internal breakdown.

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