Effects of controlled atmosphere, edible coating, and 1-methylcyclopropene on improving storage quality of ‘Bartlett’ pears after long-term storage

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Effects of controlled atmosphere, edible coating, and 1-methylcyclopropene on improving storage quality of 'Bartlett' pears after long-term storage

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ABSTRACT
Recent trends towards greater fresh market use of ‘Bartlett’ pears has increased the need to extend its storage life to prolong the packing and marketing season in the United States Pacific Northwest region. Sixteen and 38%, respectively, of control fruit developed senescence disorders following 5 and 6 months of storage at −1.1°C. Commercial standard controlled atmosphere (CA) conditions (O2 at 1.5 kPa and CO2 < 1 kPa) or edible coating (Semperfresh™, SF) prevent the appearance of senescence disorders for 5 months, but 9% and 16% of fruit, respectively, developed senescence disorders after 6 months. The combination of CA+SF completely inhibited senescence disorders for 6 months. Treatment with CA and SF, alone or in combination, maintained high-storage quality and developed ripening capacity with characteristic melting texture during storage. Senescence disorders were inhibited for 6 months by 0.3 µL L−1 1-methylcyclopropene (1-MCP), alone or combination with CA or CA+SF. In part these pears developed ripening capacity after 6 months of storage. The combination of CA+SF+1-MCP maintained the highest storage quality with dark green colour and hard firmness, which might be associated and proportional with reductions in ethylene synthesis and respiration rate after long-term storage.

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respiration and decreases ethylene production (Momen, Tatsumi, & Shimokawa, 1997; Zhou et al., 2008). However, where surface coverage is incomplete or storage temperature increases, shrivelling occurs and quality deteriorates during the marketing season.

1-Methylcyclopropene (1-MCP) inhibits ethylene development and prevents ethylene-dependent responses such as ripening and senescence of vegetable and fruit tissues (Watkins, 2002). It strengthened ‘Bartlett’ pears against the development of senescence disorders during cold storage or in ripening by inhibiting ethylene synthesis (Wang & Sugar, 2015). Our previous studies indicated that 1-MCP at rate of 0.3 μL L⁻¹ could significantly block ethylene production and resultant senescence disorders in ‘Bartlett’ pears for up to 4 months from orchards at contrasting elevations when the fruit is harvested at optimal maturity (Wang & Sugar, 2015). Unfortunately, 1-MCP has inhibited the ripening capacity of European pears (Chen & Spotts, 2005; Xie, Fang, & Wang, 2017). However, the pear industry is interested in applying 1-MCP to extend the packing season and reduce economic loss. Therefore, new 1-MCP management strategies in European pears must be investigated in combination with CA or edible coating.

The objective of this study was to investigate the effects of CA (O₂ at 1.5 kPa and CO₂ < 1 kPa), SF (0.5% active ingredient), and 1-MCP (0.3 μL L⁻¹), alone or in combination, on ethylene production, respiration rate, storage quality, senescence disorders and decay, ripening capacity, and eating quality of ‘Bartlett’ pears following 6 months of storage at −1.1°C.

Materials and methods

Fruit and treatments

‘Bartlett’ pears (Pyrus communis L.) were harvested at commercial maturity (fruit firmness ≈ 84.6 N) from mature trees in the orchard of the Mid-Columbia Agriculture Research and Extension Center (latitude 45.7°N, longitude 121.5°W, elevation 150 m, average annual rainfall ~800 mm) in Hood River, Oregon, USA in 2014 and again in 2015. Because results of the two seasons were similar, only the 2015 data are presented here. Fruit from three blocks (replications) in each orchard were mixed within each block and defect-free fruit were packed in 70 wooden boxes (~80 fruit per box) with standard perforated polyethylene liners, and then were moved into cold storage at −1.1°C and >90% relative humidity. After 24 h of storage, 30 boxes were dipped in Semperfresh™ (SF) at 0.5% active ingredient (Pace International L.L.C., Wapato, WA) at 20°C for 30 s and then air dried. Ten boxes of SF treated and 20 boxes of untreated fruit were exposed to 0.3 μL L⁻¹ 1-MCP (SmartFresh®, AgroFresh, Spring House, PA) in an airtight room (39.8 m³) with a circulation fan at −1.1°C for 24 h as recommended by the manufacturer. After treatment, 10 boxes of untreated (control), 10 boxes of SF treated (SF), and 10 boxes of 1-MCP (1-MCP) treated fruit were stored at −1.1°C. Ten boxes of untreated (CA), 10 boxes of SF treated (CA+SF), 10 boxes of 1-MCP treated (CA+1-MCP), and 10 boxes of SF+1-MCP treated (CA+SF+1-MCP) fruit were moved to a controlled atmosphere (CA) room (35.6 m²) at −1.1°C, where a semi-static O₂ concentration of 1.5 kPa was established within 3 d of harvest via purified N₂ generated from a membrane gas generator (CPA-5, Permea, St. Louis, MO) and CO₂ < 1.0 kPa was maintained by adding 0.5 kg per box of hydrated lime. O₂ and CO₂ concentrations were monitored using an O₂/CO₂ analyser (Storex, Gravendeel, Netherlands). Storage quality was evaluated at harvest and then monthly for up to 6 months. For CA, fruit were evaluated beginning at month three and then monthly for up to 6 months.

Ethylene production and respiration rates

Ethylene production and respiration rates were measured from five fruit per replication from each treatment on day 1 at 20°C after removal from cold storage. Fruit were sealed in a 3.8-l air-tight jar for 1 h at 20°C. Headspace gas samples were withdrawn with a 1-mL gas-tight syringe. Headspace ethylene concentration was measured by injecting the gas sample into a gas chromatograph (GC-8A; Shimadzu, Tokyo, Japan) equipped with a flame ionisation detector and a Porapack Q column (80/100 mesh, 3-mm in diameter, 2-m long). The carrier gas was nitrogen at a flow rate of 0.8 mL s⁻¹, the oven temperature was 90°C, and the injector and detector temperatures were 140°C. An external standard of ethylene was used for calibration. The headspace CO₂ concentration was measured using a CO₂ analyser (900,161; Bridge Analyzers Inc., Alameda, CA, USA).

Fruit flesh firmness, peel chlorophyll content, extractable juice, soluble solids content, and titratable acidity

Fruit flesh firmness and peel chlorophyll content from each treatment of 10 fruit per replication were measured on day 1 at 20°C after removal from cold storage. Peel chlorophyll content was taken on opposite sides of the equator of each fruit and estimated using a DA meter (Sinteleia, Bologna, Italy) and expressed as I₆₅₃ value. After colour determination, flesh firmness was measured using a texture analyser (GS-14, Güss
Manufacturing Ltd., Strand, South Africa) equipped with a 8-mm probe, at 9 mm of penetration and at a speed of 9 mm s\(^{-1}\). Soluble solids content and titratable acidity were determined at 20°C on 1 and 7 d after removal from cold storage. Flesh tissue (100 g) was macerated for 3 min using a juicer (6001, Acme Juicer Manufacturing Co, Sierra Madre, CA, USA). Extractable juice was measured in a 100-mL graduated cylinder. Soluble solids content of the juice was determined using a digital refractometer (PAL-1, Atago, Tokyo, Japan). Titratable acidity was determined by titrating 10 mL of juice to pH 8.1 using 0.1 M NaOH with a commercial titration system (T80/20, Schott-Gerate, Hofheim, Germany) and expressed as percentage of malic acid equivalents (grams per 100 mL juice).

Evaluation of decay and senescence disorders

Decay was evaluated at 20°C on day 1 after removal from cold storage; any pathological lesion was considered decay, which was expressed as percentage of incidence. On day 7 at 20°C, 30 fruit per replicate were evaluated for senescence scald, and then cut longitudinally and transversely to assess senescent core breakdown. The incidence of senescence disorders was expressed as percentage of fruit with either senescence scald or senescent core breakdown or both regardless of severity. The symptoms and range of severity of senescence scald and senescent core breakdown are shown in the Supplement.

Ripening capacity and sensory quality

Ripening capacity was determined as competency of fruit softening on 7 d at 20°C. Flesh firmness was determined as described above. A panel of three experienced, tasters scored sensory quality. Sensory quality (melting texture score) was scored on a five-point hedonic scale. Fruit with high, moderate, or slight melting texture were rated as 5, 4, or 3, respectively, and those rated as moderately or very firm (i.e. under ripe pears) or moderately or very mealy flesh texture (i.e. overripe pears) were rated as 2, or 1, respectively. Scale anchor points and definitions were confirmed with raters in an orientation session before the first evaluation. An average score of 3 or higher was defined as commercially acceptable.

Statistical analysis

Experiments were designed with a complete randomised design. One-way analysis of variance (ANOVA) was carried out to determine the significance of differences at \( P = 0.05 \) according to Fisher’s protected least significant difference (LSD) test. The data were subjected to analysis using SPSS software (SPSS Inc., Chicago, IL, USA).

Results

Ethylene production and respiration rates

No ethylene production was detected at harvest. Ethylene production rate in control fruit increased from 0 to 50 ng kg\(^{-1}\) s\(^{-1}\) following 6 months of storage. Compared with the control, fruit treated with SF or 1-MCP alone started to synthesise ethylene at 5 and 4 ng kg\(^{-1}\) s\(^{-1}\) after 3 and 5 months, respectively, then increased to 35 and 9 ng kg\(^{-1}\) s\(^{-1}\) after 6 months. After 6 months, the CA or CA+SF treatments increased ethylene production rate to 28 ng kg\(^{-1}\) s\(^{-1}\) and to 19 ng kg\(^{-1}\) s\(^{-1}\), respectively. CA+1-MCP or CA+SF+1-MCP treatments shut down ethylene synthesis for 4 months, which thereafter increased slightly. Respiration rate in control fruit increased from the initial 5–16 μg CO\(_2\) kg\(^{-1}\) s\(^{-1}\). Compared with the control, respiration rate in fruit treated with SF, CA, or CA+SF was suppressed during 3 months of storage, then increased to 13, 12, and 10 μg CO\(_2\) kg\(^{-1}\) s\(^{-1}\), respectively, after 6 months. 1-MCP, CA+1-MCP, or CA+SF+1-MCP treatment had a lower respiration rate than SF, CA, or CA+SF; after 6 months respiration rate increased to 8, 6, and 7 μg CO\(_2\) kg\(^{-1}\) s\(^{-1}\), respectively (Figure 1).

Fruit flesh firmness, peel chlorophyll content, soluble solids content, and titratable acidity

Compared to the initial condition, flesh firmness and I\(_{AD}\) value in the control fruit declined significantly by 10% and 37%, respectively, after 6 months. CA, SF, or CA+SF slowed losses in flesh firmness and green colour throughout the entire storage period. Further, CA+SF maintained higher flesh firmness and green colour than CA or SF alone. 1-MCP, CA+1-MCP, or CA+SF+1-MCP showed relatively higher flesh firmness and I\(_{AD}\) value than CA, SF, or CA+SF. The combination of CA+SF+1-MCP had the highest flesh firmness and I\(_{AD}\) value until 6 months of storage. No treatments affected soluble solids content during storage. Titratable acidity declined in all fruits after 6 months. Titratable acidity in control fruit decreased by 48%, while in fruit treated with CA, SF, CA+SF, 1-MCP, CA+1-MCP, or CA+SF+1-MCP it decreased by 36%, 39%, 30%, 30%, and 23%, respectively, after 6 months of storage (Figure 2).

Decay and physiological disorders

Control fruit and fruit treated with CA, SF, or CA+SF had the higher incidences of decay after 5 and 6 months. While 1-MCP, CA+1-MCP, or CA+SF+1-MCP reduced decay incidence to 0.3%, 0.5%, and 0%, respectively, after 6 months. Senescence disorders in control fruit increased to 16% and 38% after 5 and 6 months, respectively. Senescence disorders were not
detected in CA or SF treated fruit after 5 months, but senescence disorders appeared after 6 months and increased to 9% and 16%, respectively. CA+SF, 1-MCP, CA+1-MCP, or CA+SF+1-MCP completely inhibited senescence disorders over the entire storage period (Figure 3).

**Ripening capacity and eating quality**

After 5 and 6 months of storage and 7 d at 20°C, fruit treated with CA, SF, or CA+SF developed ripening capacity with flesh firmness < 23 N and extractable juice< 650 mL kg⁻¹ (Figure 4), indicating development of melting texture (Figure 5). Control fruit developed ripening capacity after 5 months, but after 6 months, flesh firmness > 24 N and extractable juice> 650 mL kg⁻¹, indicating that mealy texture had developed. Fruit treated with 1-MCP, CA+1-MCP, or CA+SF+1-MCP did not develop ripening capacity after 5 months, but flesh firmness decreased to 42 N, 42 N, and 46 N, respectively, and in part pears developed ripening capacity after 6 months. Compared to the control, fruit treated with CA, SF, CA+SF, 1-MCP, CA+1-
MCP, or CA+SF+1-MCP had higher soluble solids content and titratable acidity during ripening after 5 and 6 months.

**Discussion**

Compared with other pear cultivars in the Pacific Northwest regions, ‘Bartlett’ pears are more susceptible to loss of flesh firmness and green colour after 3 months of storage (Puig, Varga, Chen, & Mielke, 1996). The occurrence of senescence disorders, including senescent scald and senescent core breakdown, and higher fungal decay accelerate quality deterioration after long cold storage or ripening at warm temperatures (Drake, Elfving, Drake, & Visser, 2004; Wang & Sugar, 2015). The triggered of yellowing, softening, senescence disorders, and decay mainly result from the increase of ethylene synthesis after ripening chilling (Acuna, Biasi,
for 4 months of storage at −1.1°C (Wang & Sugar, 2015). The combinations of CA+1-MCP and CA+SF +1-MCP were significantly superior to 1-MCP alone in retarding ethylene production and controlling senescence disorders of ‘Bartlett’ pears. Watkins, Nock, and Whitaker (2000) indicated that the additive effectiveness of CA+1-MCP might be due to lower O₂ and ethylene action. Further, SF combined with 1-MCP in CA condition would tend to deplete more O₂ from fruit, suggesting a rapid reduction in internal O₂ concentration possible reduced oxidative metabolism and suppressed activity of 1-aminocyclopropane-1-carboxylic oxidase, thus restricting the development of senescence disorders (Bai & Plotto, 2011; Momen et al., 1997).

Green colour is an important visual indicator of the cold storage potential of ‘Bartlett’ pears. Fruit with a yellowing surface are more susceptible to shrivel, scuffing, and senescence during packing and transport (Sugar, 2007). Compared with the control, CA, SF, and 1-MCP, alone or in combinations, showed noticeable efficacies in retarding the degradation of chlorophyll (Figure 2). The retention of green colour in treated fruit might be attributed to reduction in respiration rate that reduced energy consumption (Saquet & Almeida, 2017). In this study, CA+SF +1-MCP was more effective than other treatments in establishing a modified internal atmosphere, delaying respiration rate and inhibiting the chlorophyll degradation (Figure 2). No significant differences in soluble solids content were found in CA+SF+1-MCP throughout the entire storage period. Instead, titratable acidity degradation was slowed, indicating that higher titratable acidity may be used as the carbon source in the tricarboxylic acid cycles in respiration process to prolong storage life (Ma & Chen, 2003).

‘Bartlett’ pears harvested at flesh firmness ≈ 84.5 N may develop desirable ripening capacity, higher sugar, and melting texture accompanied by an increase in aromatic volatiles after 1–3 months storage at −1.1°C (Chen, 2004). ‘Bartlett’ pears reached optimal eating quality when the ripening capacity developed to between 14 and 24 N and extractable juice was below 650 mL kg⁻¹ after removal from cold storage and fruit were held at 20°C for 5–7 d (Chen, 2004; Wang & Sugar, 2015). However, when ripening capacity > 24 N and extractable juice> 650 mL kg⁻¹, a mealy texture developed perhaps due to over-maturity or excessive long-term storage (Makkumraii et al., 2014; Wang & Sugar, 2015; Wang, Xie, & Song, 2016). In this study, control fruit developed a melting texture after 5 months, but a mealy texture after 6 months (Figures 4 and 5). Fruit treated with CA, SF, or CA+SF developed a melting texture after 5 and 6 months of storage. Unfortunately, fruit treated with 1-MCP or 1-MCP combined with CA or CA+SF failed to develop ripening capacity after 5 months. It

**Figure 5.** Sensory score of textural quality influenced by CA, SF, or1-MCP of ‘Bartlett’ pears after 5 and 6 months of storage at −1.1°C and 7 d at 20°C. CA condition at O₂1.5 kPa and CO₂ < 1 kPa; SF at 0.5% active ingredient; 1-MCP at 0.3 μL L⁻¹. Values are presented as the means ± SD, n = 3. Different letters indicate significant differences between treatments after 5 (a–c) and 6 months (A –D) storage according to Fisher’s protected LSD test at P = 0.05.
is interesting to note that after 6 months, some of these pears recovered ripening capacity with extractable juice close to 650 mL kg⁻¹. Among the SF, CA +SF, and CA+SF+1-MCP treatments, CA+SF+1-MCP maintained the highest levels of extractable juice, soluble solids content, and titratable acidity after 6 months of storage, indicating that SF coating might act as a water vapour barrier to prevent fruit from shrivelling, thus extending pears quality. SF coating retains water vapour inside fruit due to the relative low permeability of the coating film (Feng et al., 2004; Zhou et al., 2011, 2008). The loss of water vapour through the cuticle, rather than the pores from the fruit interior to the ambient air continues at the onset of storage (Amarante, Banks, & Ganesh, 2001). Protected water availability in fruit affected its metabolism, reduced losses in soluble solids content and titratable acidity, and thus retained higher eating quality (Santesteban & Royo, 2006). Therefore, CA +SF+1-MCP may be considered as a complementary strategy to controlling senescence disorders development for over-matures ‘Bartlett’ pears in certain hot years.

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