



# The Effect of Aminoethoxyvinylglycine and Dynamic Controlled Atmosphere on the Storage of ‘Bartlett’ Pear

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## Abstract

Storage trials of 4 and 8 months’ duration, using ‘Bartlett’ pear (*Pyrus communis*) fruit treated with and without aminoethoxyvinylglycine (AVG) and stored using ultra low oxygen (ULO) storage (1.5 kPa O<sub>2</sub>) versus dynamic controlled atmosphere (DCA) ( $\approx 0.6\text{--}0.7$  kPa O<sub>2</sub>) based on chlorophyll fluorescence were conducted over 2 years. AVG applied preharvest and DCA storage produced pears with significantly lower respiration, ethylene, acetaldehyde, ethyl acetate and ethanol post-storage compared to the other treatment combinations. Lower volatiles reflected a higher level of fruit quality. AVG+DCA also exhibited greater green color and firmness retention than the other treatment combinations. There were few disorders in both years of study, with no correlation with field and storage treatments, with the exception of pear scuffing, which was only present in year 2. The incidence of scuffing was positively associated with both fruit softening and yellowing, with DCA+AVG showing the lowest incidence (10%) and ULO+control, the highest (65%). Softening occurred during the shelf life period, as required, and was not an issue for any treatment combination. However, uneven degreening was a concern for fruit treated with DCA+AVG (mainly when firmness at harvest was >85 N). Future research on higher maturity levels at harvest or reduced AVG rates could address this concern.

**Keywords** Chlorophyll fluorescence · Ethylene · Lower oxygen limit · Pear scuffing · Ultra low oxygen

## Introduction

‘Bartlett’ (‘Williams Bon Chrétien’) is the second most popular stored European pear cultivar with storage recommendations for 13 pear-growing regions worldwide (Prange 2022). Unfortunately, its storage potential is quite short, i.e., 1–3 months in refrigerated air. However, controlled atmosphere (CA) storage can increase this period to 4 months (Kupferman 2003). In recent years, chlorophyll fluorescence based dynamic controlled atmosphere (DCA-CF) technology, which lowers the storage O<sub>2</sub> to just above the low O<sub>2</sub> limit (LOL) of the fruit (Prange 2022; Wright et al. 2012), has been used successfully to extend the storage period of ‘Bartlett’ even further in some production regions, e.g., Argentina (Prange et al. 2011) and Australia

(M. Hall, Personal communication), by prolonging green color retention, reducing disorders and allowing fruit to ripen and soften evenly. However, in Nova Scotia, both CA and DCA appear to be less effective than in other regions, allowing some uneven ripening after 4 months of storage.

One possible solution may be to combine DCA with a preharvest treatment of aminoethoxyvinylglycine (AVG). Low oxygen during fruit storage reduces the fruit respiration rate and the production of ethylene. AVG is a growth regulator that inhibits 1-aminocyclopropane carboxylic acid (ACC) synthase activity and therefore ethylene production (Venburg et al. 2008). It is applied preharvest to slow fruit maturation and reduce preharvest fruit drop. Research on the effect of both preharvest and postharvest application of AVG on ‘Bartlett’ pear has shown that there can be desirable improvements in fruit quality, but this can vary depending on several factors, e.g., the method of application (preharvest versus postharvest), AVG concentration, maturity of the fruit and time of application (days before harvest) (Andreotti et al. 2004; Batur and Çetinbaş 2017; Clayton et al. 2000; Curry 2008; Dussi et al. 2002; Emre et al. 2019; Ness and Romani 1980; Romani et al. 1982; Wang et al. 2016). For example, Wang et al. (2016) examined the ef-

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fects of three preharvest AVG spray rates and timing on the storability of 'Bartlett' pear fruit at three harvest maturities (corresponding to three firmness values: Harvest 1 = 84.5 N, Harvest 2 = 76.0 N and Harvest 3 = 73.4 N) in terms of ethylene production, storage quality and ripening capacity during 5 months of refrigerated air storage at  $-1.1^{\circ}\text{C}$ . The authors concluded that AVG had no effect on Harvest 3 fruit, which were likely over-mature, but that AVG applied to Harvest 1 fruit at  $60\text{ mg L}^{-1}$  1 week before harvest improved storability, i.e., it suppressed ethylene production, respiration rate, firmness loss, green loss and development of senescence disorders, and it maintained ripening capacity in both Harvest 1 and Harvest 2 fruit. Applying AVG at a higher concentration,  $120\text{ mg L}^{-1}$ , 1 week before harvest also had similar effects on storage quality, but delayed ripening capacity by 1 month.

Several studies have investigated the interaction of standard CA ( $\text{O}_2 \geq 2\text{ kPa}$ ) or ULO-CA ( $\text{O}_2$  ca.  $1.0\text{--}1.9\text{ kPa}$ ) with AVG on postharvest quality and disorder control of various apple cultivars with either no benefit or some benefit, depending on the cultivar (Prange 2022). One study (Wendt et al. 2022) examined the effects of preharvest AVG used alone or in combination with either CA or DCA on storage quality of 'Galaxy Gala' apples. The authors concluded that the combination of AVG preharvest treatment and DCA technology was the best method for providing excellent quality apples with few physiological disorders.

Research on the effect of the combined use of AVG and CA on pears is limited (Prange 2022). Dong (2020) examined the effect of AVG combined with various CA conditions on the development of superficial scald in 'd'Anjou' pears. He found that AVG applied 1 week before harvest at  $60$  or  $120\text{ mg L}^{-1}$  resulted in reductions in scald compared with the untreated control, after 3 and 5 months of refrigerated air storage. However, the incidence of superficial scald in all treatments increased throughout the storage period and reached 100% by month 7. According to Dong (2020), oxygen concentrations of  $0.5$  and  $1\text{ kPa}$  inhibited the development of superficial scald, with fruit stored at a concentration of  $0.5\text{ kPa}$  remaining free of scald over the entire storage period and fruit stored at  $2\text{ kPa}$  showing 68% scald at 6 months and 90% after 10 months. Pears treated with AVG at  $60$  and  $120\text{ mg L}^{-1}$  and stored at a concentration of  $0.8\text{ kPa}$  were scald free following 10 months of storage.

The purpose of this study was to determine the effect of using AVG applied preharvest and DCA storage on the postharvest quality of 'Bartlett' pears.

## Materials and Methods

Trials investigating field applications of AVG (ReTain®, 15% AVG, Valent Canada, Guelph, ON, Canada), combined with DCA, were conducted over 2 consecutive years. The protocol used for these trials varied slightly between years, as described below.

### Grower Sites

Fruit were obtained in each of the 2 years from the same four commercial 'Bartlett' pear (*Pyrus communis*) orchards, all located in the Annapolis Valley, Nova Scotia, Canada. Fruit from all sites were sampled frequently before the harvest date in each of the 2 years; a firmness level of  $85\text{ N}$  (details below) was targeted; however, because all sites were harvested on the same day in both years, some sites fell slightly below and others slightly above the target firmness on the day of harvest. General year-to-year weather data was collected from the nearby Environment and Climate Change Canada weather station located in Kentville, NS. None of the sites used were irrigated in either year.

### Field Treatments

At each site, four pear trees were randomly selected each year. Two trees were sprayed with AVG mixed with a surfactant (Sylgard®, 0.05% v/v, Dow Corning Canada Inc., Georgetown, ON, Canada) and two trees were left unsprayed to act as a control treatment. In year 1, the trees were treated with a half rate® ( $0.42\text{ kg ha}^{-1}$  or  $66\text{ mg AVG L}^{-1}$ ) and the fruit were harvested 24 h after application; in year 2, the trees were treated with a full rate ( $0.83\text{ kg ha}^{-1}$  or  $132\text{ mg AVG L}^{-1}$ ) and harvested 7 days after application.

### Harvest Assessment

In year 1, 10 control fruit from each site (total pear  $n=40$ ) were harvested individually and destructively measured to assess maturity at harvest. In year 2, five control and five AVG fruit from each site were sampled in the same way (total pear  $n=40$ ). For all destructively measured pears, individual fruit mass (g) was measured using a scale (CP 4202 S, Sartorius, Göttingen, Germany). Chlorophyll levels on both the sun and shade sides of each fruit were measured using a delta absorbance (DA) meter (Sintéleia  $\chi$ , Bologna, Italy). After  $\cong 3\text{ mm}$  of skin and cortex tissue were removed from both the sun and shade sides of each fruit with a mandolin, firmness levels (N) were measured using a digital penetrometer (Chatillon DFIS50; Ametek TCI Division, Largo, FL, USA) fitted with a standard 8 mm pear tip. A garlic press was used to obtain a juice sample from

each fruit. A hand-held temperature-compensated digital refractometer (Atago Co., Tokyo, Japan) was used to measure soluble solids content (SS, %). Titratable acidity (TA) was measured in year 1 control treatment fruit only. TA levels were measured with a Buret/Dispenser (Brinkmann Model 350; Metrohm, Herisau, Switzerland) using 2 mL of juice sample, 0.1 M NaOH and a pH 8.1 end-point as indicated by phenolphthalein. In addition, fruit harvested for long-term storage were individually labelled and their non-destructive initial mass (g) and DA levels were recorded. In year 1 and 2, this required an extra 30 fruit and 40 fruit per grower per treatment, respectively.

An additional five fruit of known mass from each grower were placed in a 4 L respiration jar, sealed at room temperature ( $\approx 20^{\circ}\text{C}$ ) and kept sealed for approximately 15 h. Headspace  $\text{O}_2$  and  $\text{CO}_2$  levels were measured using a 2 mL sample injected into a gas analyzer (International Controlled Atmosphere Ltd., ICA40 system, Tonbridge, UK). Ethylene levels were measured using a 1 mL sample injected into an analytical gas chromatograph (GC) (Model 211; Carle Instruments, Anaheim, CA, USA) equipped with a 2.4 m activated-alumina-packed column (3.18 mm o.d.) and a flame ionization detector (FID). Finally, the anaerobic respiration volatiles acetaldehyde (AA), ethanol (EtOH) and ethyl acetate (EA) were also measured using a 1 mL sample injected into a GC (Varian 3400, Walnut Creek, CA, USA) with a SupelcoWax 10 column (30 m  $\times$  0.53 mm i.d., 1.0  $\mu\text{m}$  coating thickness) as described by DeLong et al. (2004).

### Storage Treatments

All fruit were stored at  $-1^{\circ}\text{C}$ . Two CA storage treatments were employed: 1. ULO (1.5 kPa  $\text{O}_2$ ,  $<0.7$  kPa  $\text{CO}_2$ ), 2. DCA. In year 1, fruit were stored for 4 months. In year 2, twice the number of cabinets were used and half the cabinets were opened and the fruit assessed at 4 months and the remainder were processed after 8 months. DCA lower  $\text{O}_2$  levels were detected using the chlorophyll fluorescence-based HarvestWatch™ System (Satlantic, Canada; distributed by Isolcell S.p.A., Italy), as opposed to ethanol or respiratory quotient (RQ) based forms of DCA. Oxygen levels were set 0.2 kPa above the LOL. In both years, this resulted in an  $\text{O}_2$  level of  $\approx 0.6$  or 0.7 kPa  $\text{O}_2$  while  $\text{CO}_2$  levels were  $<0.2$  kPa. Individual CA storage treatments for a given removal time consisted of storage in single-bushel, top-loading CA cabinets fitted with a water seal. In total, 10 control and 10 AVG fruit from each of the four growers were labelled and stored in each cabinet; Control and AVG fruit were separated using a divider. In addition to this, a HarvestWatch™ kennel containing one control fruit and one AVG fruit from each grower ( $n=8$ ) was also placed in each cabinet, for a total of 88 fruit per cabinet. Oxygen and

$\text{CO}_2$  levels in each chamber were monitored and controlled using a David Bishop Instruments Oxystat 2002 system (Bacharach Europe, Warwickshire, UK).

### Storage Assessment

After storage, a fruit assessment was performed on day 1 (initial) and after 4 days at  $20^{\circ}\text{C}$  (day 4—shelf life). The fruit mass and chlorophyll level (sun and shade) of all 10 fruit per grower/treatment combination were assessed, as described above, on day 1; five fruit per grower/treatment combination were assessed on day 4. A non-destructive color assessment (Spectrophotometer CM2600d, Konica Minolta, Tokyo, Japan) was performed on 10 fruit per grower/treatment combination on day 1 and on 5 fruit on day 4. Color was expressed using the Lab Color Space which comprises three axes: L—darkness to lightness (0–100), a—greenness to redness (–128 to 127), b—blueness to yellowness (–128 to 127). Five fruit per treatment/grower combination were destructively assessed for firmness (sun and shade), SS and TA on day 1 and 4 as described above. Headspace respiration, ethylene and anaerobic respiration volatiles were assessed using five fruit from different grower/treatment combinations on both day 1 and day 4 during shelf life as described above. Fruit were also assessed for storage disorders.

### Statistical Analyses

Data were analyzed using multi-factor ANOVAs and t-tests from the R software suite (R Development Core Team 2022). The constant variance and normal distribution assumptions were tested using a residual versus fits plot and a normal quantile-quantile plot, respectively. In instances where one or more of these assumptions were violated, transformed data was used and then a back-transformation was performed. For significant main effects and interactions, treatment means were compared via a Tukey pairwise comparison (emmeans package). Treatment differences were considered significant if  $P \leq 0.05$ .

## Results and Discussion

### Weather, Harvest Assessment and Year Differences

The base  $5^{\circ}\text{C}$  growing degree day ( $\text{GDD}_5$ ) heat units from June to August was 1304 in year 1 and 1282 in year 2. The 15-year average is 1272. Year 1 and year 2 received 193 mm and 250 mm of rain over the same time period, respectively. The 15-year average is 286 mm (Kentville, data from Environment and Climate Change Canada 2022). The harvest date, based on fruit firmness, was August 28 in year 1 and

**Table 1** Fruit parameters at harvest by year and treatment averaged across four growers/blocks. Aminoethoxyvinylglycine (AVG) was applied 24 h and 7 days before harvest in years 1 and 2, respectively

| Trt           | Mass (g) | $\Delta A$ | Firm (N) | SS (%) | mL O <sub>2</sub> (kg h) <sup>-1</sup> | mL CO <sub>2</sub> (kg h) <sup>-1</sup> | $\mu\text{L C}_2\text{H}_4$ (kg h) <sup>-1</sup> |
|---------------|----------|------------|----------|--------|----------------------------------------|-----------------------------------------|--------------------------------------------------|
| <b>Year 1</b> |          |            |          |        |                                        |                                         |                                                  |
| Control       | 128.0    | 1.46       | 82.3     | 9.6    | -7.35                                  | 6.74                                    | 0.0                                              |
| AVG           | 130.2    | 1.45       | NA       | NA     | NA                                     | NA                                      | NA                                               |
| <b>Year 2</b> |          |            |          |        |                                        |                                         |                                                  |
| Control       | 168.4*   | 1.48*      | 85.9     | 10.3   | -6.09*                                 | 6.36*                                   | 0.04*                                            |
| AVG           | 154.2*   | 1.49*      | 85.4     | 10.0   | -4.88*                                 | 5.09*                                   | 0.00*                                            |

Significantly different factor level averages are denoted with an asterisk (\*). Comparisons complicated by interactions are denoted by a superscripted letter with details given in a footnote

September 3 in year 2. Due to AVG treatment timing (24 h vs. 7 days preharvest, respectively) and dosage differences (1/2 rate vs full rate, respectively) between year 1 and 2, the 2 years were analyzed independently. This study was not designed to determine the effect of the different protocols as any differences will be confounded by the potential year effect. Instead, the focus of both years was to investigate the combined use of a field application of AVG and low oxygen DCA storage.

Fruit quality parameters (mass, chlorophyll, firmness and SS) at harvest in year 1 and 2 are shown in Table 1. Fruit were larger in year 2 relative to year 1 ( $p < 0.001$ ), likely on account of the higher rainfall levels (30% more than in year 1). In year 1 there was no difference in fruit size or DA readings across treatments; however, in year 2, an ANOVA suggested that AVG treated fruit were smaller and had slightly higher chlorophyll levels (i.e.,  $\Delta A$ ) relative to control fruit ( $p < 0.01$ ). In both years and treatments, a paired t-test showed that chlorophyll levels were higher on the sun side than the shade side of the fruit ( $p < 0.001$ ) (Table 1). T-tests showed that the year 1 “control” fruit had lower

SS and lower firmness than year 2 “control” fruit (Table 1,  $p < 0.05$ ). Fruit TA levels in year 1 “control” fruit ( $n = 40$ ) averaged 355 mg of malic acid equivalent per 100 mL of juice. No anaerobic respiration volatiles were detected in the fruit headspace at harvest, regardless of year or treatment. In year 1, no ethylene was detected in control fruit; year 1 AVG fruit were not measured. In year 2, when AVG was applied 1 week before harvest, trace ethylene levels were detected in “control”, but not treated fruit. Additionally, AVG treated fruit showed reduced respiration levels relative to “control” fruit at harvest in year 2 (Table 1).

### Post Storage: Fruit Quality

The year 1 trial, when AVG was applied only 24 h before harvest, will be addressed first. In year 1, field and storage treatments did not affect fruit mass loss. Fruit showed decreases in mass, chlorophyll, firmness and acidity over the course of the 4-day shelf life, while SS levels increased. In terms of  $L^*a^*b$  color, fruit became lighter (higher L), less green (lower a) and yellower (higher b) (Table 2). The AVG

**Table 2** Year 1 post-controlled atmosphere (CA) storage pear fruit quality parameters broken down by day (initial [Day 1] vs. shelf life [Day 4]), field treatment (control vs. aminoethoxyvinylglycine [AVG]) and storage treatment (ultra low oxygen [ULO] vs. dynamic controlled atmosphere [DCA]) after 4 months of CA storage. AVG was applied 24 h before harvest in year 1

|                   | Mass loss % | Chlorophyll<br>(ΔA) loss (%) | Color |                    |                   | Firm (N) | SS (%) | TA (mg/100 mL)   |
|-------------------|-------------|------------------------------|-------|--------------------|-------------------|----------|--------|------------------|
|                   |             |                              | L     | a                  | b                 |          |        |                  |
| Day               |             |                              |       |                    |                   |          |        |                  |
| Day 1 (initial)   | 1.27*       | 6.8*                         | 62.2* | −13.5*             | 32.1*             | 77.9*    | 11.3*  | 342*             |
| Day 4 (shelf)     | 4.95*       | 56.8*                        | 68.1* | −7.5*              | 41.1*             | 18.7*    | 12.0*  | 291*             |
| Field treatment   |             |                              |       |                    |                   |          |        |                  |
| Control           | 2.93        | 33.4                         | 65.7* | −10.5              | 37.1 <sup>c</sup> | 48.1     | 11.5*  | 315              |
| AVG               | 3.28        | 30.2                         | 64.6* | −10.4              | 36.0 <sup>c</sup> | 48.5     | 11.8*  | 318              |
| Storage treatment |             |                              |       |                    |                   |          |        |                  |
| ULO               | 2.94        | 37.6 <sup>a</sup>            | 66.4* | −9.0 <sup>b</sup>  | 37.2*             | 48.1     | 11.4*  | 306 <sup>d</sup> |
| DCA               | 3.27        | 26.0 <sup>a</sup>            | 64.0* | −12.0 <sup>b</sup> | 36.0*             | 49.0     | 11.8*  | 326 <sup>d</sup> |

Significantly different factor level averages are denoted with an asterisk (\*). Comparisons complicated by interactions are denoted by a superscripted letter with details given in a footnote

<sup>a</sup>Storage  $\times$  Day = 0.003. No difference in  $\Delta A$  loss on day 1, but ULO (68%) > DCA (45%) on day 4

<sup>b</sup>Storage  $\times$  Day = 0.003. No difference in “a” on day 1, but ULO (-4.9) > DCA (-10.1) on day 4. Lower “a” = greener

<sup>c</sup>Field  $\times$  Day = 0.03. No difference in “b” on day 1, but Control (42.0) > AVG (40.1) on day 4. Higher “b” = yellower

<sup>d</sup>Storage  $\times$  Day = 0.01. No difference in TA on day 4, but DCA (362.9) > ULO (321.0) on day 1

field treatment had little effect on fruit quality parameters in year 1, except that treated fruit had slightly higher SS levels, were darker (lower L) and were slightly less yellow (lower b), but the latter only applied to fruit assessed after their 4-day shelf life (Table 2). The storage treatment showed that DCA fruit had more chlorophyll relative to ULO, but only after the 4-day shelf life. DCA fruit also had higher SS levels. Acid retention was higher in DCA fruit, but this difference dissipated over the 4-day shelf life. Finally, in terms of color, DCA fruit were darker (lower L) and less yellow (lower b). The DCA fruit were also greener (lower a) compared to ULO fruit, but only on day 4 of the shelf life (Table 2).

The trial conducted in year 2 was similar to year 1, with two notable exceptions: 1. AVG was applied 7 days as opposed to 24h before harvest and at the full rate as opposed to the half rate, 2. There were two removals (4 month and 8 month). The effect of the field and storage treatments in terms of the initial (day 1) and shelf life (day 4) fruit quality is shown in Table 3. As in year 1, mass loss and SS both increased over the course of shelf life in year 2. TA decreased during shelf life, but only after the 4-month removal. TA levels remained unchanged after the 8-month removal. The fruit lost chlorophyll and firmness during shelf life. With

respect to fruit color, the  $L^*a^*b$  values indicate that fruit color became lighter (higher "L"), less green (higher "a") and more yellow (higher "b") (Table 3). Removal time (4 vs. 8 months) did not affect firmness or mass loss, while SS and TA levels both decreased with the longer storage time. Chlorophyll loss was greater at 8 than 4 months for the day 1 fruit only. Fruit treated with AVG became lighter but control fruit did not. Fruit became both more green and yellow with the longer storage duration (Table 3). It seems unlikely that the fruit actually became greener with longer storage duration. It should be kept in mind that this breakdown includes fruit color averaging over both day 1 and day 4 of the shelf life; in other words, it includes the way in which the fruit changed color during the shelf-life period. This is a period of dramatic color change, hence the average value may not reflect the changes that occurred during cold storage, which were much less pronounced. Instead, this finding likely reflects differences in the way pears change color after the shorter and longer storage period. Specifically, the older and more lethargic 8 month fruit had lower energy and metabolism levels and de-greened more slowly than the 4 month fruit.

The effect of the field treatment in year 2 resulted in multiple interactions. AVG increased mass loss in DCA fruit but

**Table 3** Year 2 post-controlled atmosphere (CA) storage pear fruit quality parameters broken down by day (initial [Day 1] vs. shelf life [Day 4]), Removal (4 vs. 8 month), field treatment (control vs. aminoethoxyvinylglycine [AVG]) and storage treatment (ultra low oxygen [ULO] vs. dynamic controlled atmosphere [DCA]). AVG was applied 7 days before harvest in year 2

|                   | Mass loss %       | Chlorophyll<br>(ΔA) loss (%) | Color             |                   |                   | Firm (N)          | SS (%) | TA (mg/100 mL)   |
|-------------------|-------------------|------------------------------|-------------------|-------------------|-------------------|-------------------|--------|------------------|
|                   |                   |                              | L                 | a                 | b                 |                   |        |                  |
| Day               |                   |                              |                   |                   |                   |                   |        |                  |
| Day 1 (initial)   | 1.57*             | 8.9*                         | 59.5*             | −9.7*             | 30.8*             | 73.9*             | 10.9*  | 207 <sup>h</sup> |
| Dag 4 (shelf)     | 5.32*             | 53.0*                        | 63.3*             | −5.4*             | 38.6*             | 21.4*             | 11.3*  | 201 <sup>h</sup> |
| Removal           |                   |                              |                   |                   |                   |                   |        |                  |
| 4 Month           | 3.25              | 27.7 <sup>b</sup>            | 60.6 <sup>c</sup> | −6.9*             | 33.4*             | 47.6              | 11.3*  | 222*             |
| 8 Month           | 3.46              | 34.2 <sup>b</sup>            | 62.0 <sup>c</sup> | −8.2*             | 36.0*             | 47.6              | 10.9*  | 186*             |
| Field treatment   |                   |                              |                   |                   |                   |                   |        |                  |
| Control           | 3.05 <sup>a</sup> | 38.7*                        | 61.2              | −7.6 <sup>d</sup> | 34.7 <sup>e</sup> | 45.8 <sup>f</sup> | 11.2   | 191 <sup>i</sup> |
| AVG               | 3.65 <sup>a</sup> | 23.2*                        | 61.4              | −7.5 <sup>d</sup> | 34.7 <sup>e</sup> | 49.4 <sup>f</sup> | 11.0   | 216 <sup>i</sup> |
| Storage treatment |                   |                              |                   |                   |                   |                   |        |                  |
| ULO               | 3.20 <sup>a</sup> | 36.2*                        | 61.7              | −5.9*             | 34.9              | 45.4 <sup>g</sup> | 11.1   | 209 <sup>j</sup> |
| DCA               | 3.49 <sup>a</sup> | 25.8*                        | 60.9              | −9.2*             | 34.5              | 49.4 <sup>g</sup> | 11.2   | 199 <sup>j</sup> |

Significantly different factor level averages are denoted with an asterisk (\*). Comparisons complicated by interactions are denoted by a superscripted letter with details given in a footnote

<sup>a</sup>Field  $\times$  Storage = 0.04. No difference in mass loss in control fruit, but DCA (4.0%) > ULO (3.4%) for AVG fruit

<sup>b</sup>Day  $\times$  Removal = 0.008. No difference in  $\Delta A$  loss on day 4, but 8 month (16.0%) > 4 month (1.9%) on day 1

<sup>c</sup>Field  $\times$  Removal = 0.04. No difference in control "L" between removals, but AVG 8 month (62.5) > 4 month (60.2). Higher "L" = lighter

<sup>d</sup>Field  $\times$  Day: Removal < 0.001. Difference in control and AVG "a" on account of 4 month, day 4 assessment: Control (-1.8) > AVG (-6.2). Lower "a" = less green

<sup>e</sup>Field  $\times$  Day: Removal = 0.02. Difference in control and AVG "b" on account of 4 month, day 4 assessment: Control (38.6) > AVG (36.0). Higher "b" = yellower

<sup>f</sup>Field  $\times$  Storage = 0.01. No difference in firm for ULO fruit, but AVG (11.9) > control (10.3) for DCA fruit

<sup>g</sup>Field  $\times$  Storage = 0.01. No difference in firm for control fruit, but DCA (11.9) > ULO (10.4) for AVG fruit

<sup>h</sup>Timing  $\times$  Removal = 0.02. No difference in TA at 8 months, but initial (230.4) > shelf (212.9) at 4 months

<sup>i</sup>Field  $\times$  Removal = 0.02. No difference in TA at 4 months, but AVG (204.6) > control (167.5) at 8 months

<sup>j</sup>Storage  $\times$  Timing = 0.03. No difference in TA on day 1, but ULO (202.4) > DCA (175.0) on day 4

not ULO fruit. The mass loss observed in fruit postharvest is primarily due to water loss. It is speculated that the difference in pear mass loss observed between treatments may be attributable to differences in the state of the pear's waxy cuticle (Lara et al. 2019). In a less mature fruit, the waxy bloom is made up of platelets that stand on edge and may better facilitate gas and water movement. As a fruit matures and senesces, the nature of this bloom changes and the wax melts and can become "greasy," possibly inhibiting water flow out of the fruit. AVG also increased firmness relative to control fruit, but this was only observed in DCA fruit. AVG did not affect acid retention at the 4-month removal, but an improvement was noted at the 8-month removal. The SS content was not affected by the field treatment. In terms of color, the field treatment had no effect on lightness (L), but AVG fruit were both greener (lower "a" value) and less yellow (lower "b" value) than control fruit, but only for the 4-month shelf life (day 4) fruit (Table 3). As for the storage treatments, DCA fruit showed increased mass loss relative to ULO fruit, but only for the AVG fruit. DCA fruit had less chlorophyll loss than ULO fruit. DCA improved firmness relative to ULO, but this was restricted to the AVG fruit. Storage treatment did not affect SS content. Slightly higher acidity levels were associated with ULO compared to DCA in year 2, but only with the 4-day shelf life (Table 3).

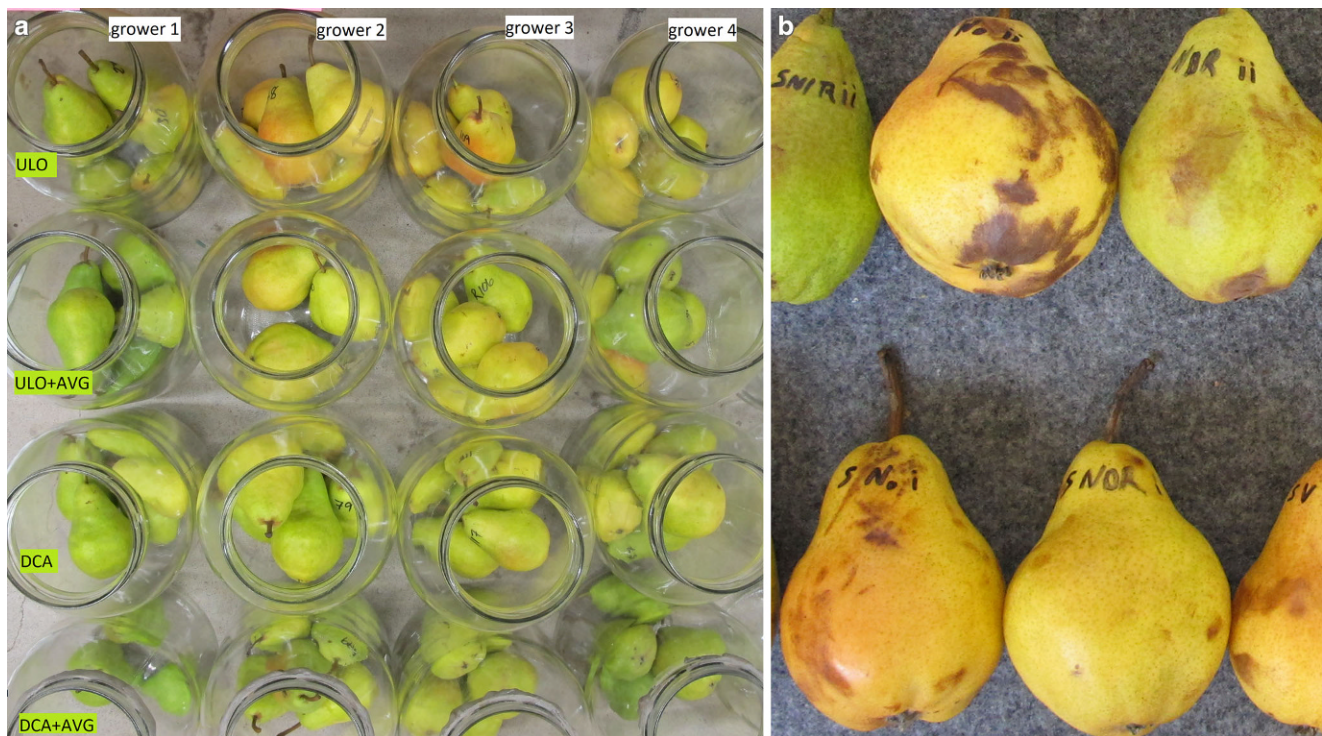
Although 85 N firmness is considered the optimum firmness for pears entering storage, fruit are expected to soften considerably within days after they are sold to the consumer to be considered edible. Recommendations from the University of California Davis (Davis, California) postharvest department suggest that, in general, pears should have a buttery texture with a firmness between 9 to 18 N (Mitcham et al. 1996). Porritt (1965) suggests that 'Bartlett' pears should have a soft, melting texture with a firmness slightly less than 13 N. The overall average firmness, which includes fruit directly out of storage and after the 4-day shelf life, was found to be slightly higher in the combined DCA and AVG treatment in year 2, when AVG was applied 7 days before harvest and fruit were stored for as long as 8 months (Table 3). This finding suggests that the DCA + AVG treatment combination could be considered to have a longer shelf life than other combinations. Firmness results across all field and storage treatments showed that fruit averaged 71 to 80 N firmness on day 1 of the shelf life (down slightly from  $\approx 85$  N at harvest) and softened considerably, to approximately 18 N after only 4 days of shelf life, with no major treatment interactions noted during the post-storage shelf life period (Tables 2 and 3). The same was true for fruit color change during the shelf life. Although the DCA and AVG treatments produced fruit that were darker and greener when they first came out of storage, no major treatment interactions were noted in the pears' propensity to both lighten and turn yellower post-storage based on their

L-a-b color scores (Tables 2 and 3). It should be noted, albeit anecdotally, that the rate of yellowing during the shelf life varied across the field and storage treatment combinations. The constraints of the trial meant that only one harvest date was used in each year. Because the trial used multiple sites, harvesting was done when the four sites averaged 85 N firmness. In both years, this meant that firmness was above 85 N at some sites and lower at others. The variability in the rate of color change was more pronounced in the sites that were harvested when firmness exceeded 85 N and less pronounced at the sites that were harvested at a firmness level below 85 N. Such color contrasts due to site are discernible in Fig. 1a. Although the statistics related to color do not capture such nuances, the level of greenness in the greener fruit from the DCA + AVG treatment combination surpassed other treatments. Immature fruit harvested at 85 N that were from the DCA + AVG treatment were less likely to yellow within an acceptable amount of time during the shelf life period.

### Post Storage: Metabolism and Volatiles

In year 1, fruit ethylene and respiration levels after 4 months of storage increased during the shelf life period; anaerobic respiration volatiles were detected on day 4 but only negligible levels were measured on day 1 (Table 4). AVG suppressed the rise in ethylene relative to untreated control fruit over the course of the shelf life but did not affect respiration levels or anaerobic respiration volatiles. DCA suppressed respiration, ethylene and all anaerobic respiration volatiles relative to fruit stored under ULO (Table 4).

Similar results were found in year 2, with subtle differences (Table 5). An image of the fruit in the respiration jars, showing a range of colors across grower and treatment combinations, is provided in Fig. 1a. As in year 1, all year 2 headspace gas levels measured increase over the course of the 4-day shelf life. There was no difference in respiration levels ( $\text{CO}_2$ ) between storage durations as measured on day 1 (initial), but day 4 (shelf) levels were lower after 8 months compared to 4 months. Ethylene levels increased in DCA fruit but decreased in ULO fruit. Levels of all anaerobic respiration volatiles (acetaldehyde, ethanol and ethyl acetate) increased with storage duration. Field-treated AVG fruit showed reduced levels of respiration, ethylene and anaerobic respiration volatiles relative to control fruit, except for acetaldehyde, which was not different in Field treatments on day 1 after removal, but was lower in AVG relative to control fruit on day 4. Levels of ethylene and all anaerobic respiration volatiles were lower in DCA than in ULO fruit. Respiration levels were complicated by an interaction that showed lower  $\text{CO}_2$  levels in DCA than in ULO fruit after 4 months, but no difference between storage treatments after 8 months (Table 5). The quality of the fruit



**Fig. 1** **a** Pear fruit placed in respiration jars on day 3 of the shelf life after 4 months of storage in year 2 of the study; **b** pear fruit showing varying levels of “scuffing” (brown marks) after 8 months of storage and an extended shelf-life period (8 days)

**Table 4** Year 1 post-controlled atmosphere (CA) storage pear headspace levels broken down by day (initial [Day 1]) vs. shelf life (Day 4), field treatment (control vs. aminoethoxyvinylglycine [AVG]) and storage treatment (ultra low oxygen [ULO] vs. dynamic controlled atmosphere [DCA]). AVG was applied 24 h before harvest in year 1. Fruit were stored for 4 months. CO<sub>2</sub> and ethylene field and storage treatment averages are for day 1 and 4 combined; storage and field treatment levels of anaerobic respiration volatiles (acetaldehyde, ethyl acetate and ethanol) were based on day 4 values alone, as negligible levels were found on day 1

|                          | mL CO <sub>2</sub> (kg h) <sup>-1</sup> | Ethylene<br>μL C <sub>2</sub> H <sub>4</sub> (kg h) <sup>-1</sup> | Acetaldehyde<br>μL C <sub>2</sub> H <sub>4</sub> O (kg h) <sup>-1</sup> | Ethyl acetate<br>μL C <sub>4</sub> H <sub>8</sub> O <sub>2</sub> (kg h) <sup>-1</sup> | Ethanol<br>μL C <sub>2</sub> H <sub>6</sub> O (kg h) <sup>-1</sup> |
|--------------------------|-----------------------------------------|-------------------------------------------------------------------|-------------------------------------------------------------------------|---------------------------------------------------------------------------------------|--------------------------------------------------------------------|
| <b>Day</b>               |                                         |                                                                   |                                                                         |                                                                                       |                                                                    |
| Day 1 (initial)          | 7.6 <sup>b</sup>                        | 38.2 <sup>b</sup>                                                 | 0 <sup>b</sup>                                                          | 0.2 <sup>b</sup>                                                                      | 0.2 <sup>b</sup>                                                   |
| Day 4 (shelf)            | 17.0 <sup>a</sup>                       | 93.7 <sup>a</sup>                                                 | 302 <sup>a</sup>                                                        | 20.9 <sup>a</sup>                                                                     | 9.5 <sup>a</sup>                                                   |
| <b>Field treatment</b>   |                                         |                                                                   |                                                                         |                                                                                       |                                                                    |
| Control                  | 12.6 <sup>a</sup>                       | 82.4 <sup>a</sup>                                                 | 315 <sup>a</sup>                                                        | 21.2 <sup>a</sup>                                                                     | 10.0 <sup>a</sup>                                                  |
| AVG                      | 12.0 <sup>a</sup>                       | 39.4 <sup>b</sup>                                                 | 290 <sup>a</sup>                                                        | 20.6 <sup>a</sup>                                                                     | 8.9 <sup>a</sup>                                                   |
| <b>Storage treatment</b> |                                         |                                                                   |                                                                         |                                                                                       |                                                                    |
| ULO                      | 14.3 <sup>a</sup>                       | 87.0 <sup>a</sup>                                                 | 517 <sup>a</sup>                                                        | 35.9 <sup>a</sup>                                                                     | 15.3 <sup>a</sup>                                                  |
| DCA                      | 10.3 <sup>b</sup>                       | 39.4 <sup>b</sup>                                                 | 88 <sup>b</sup>                                                         | 5.9 <sup>b</sup>                                                                      | 3.7 <sup>b</sup>                                                   |

Significantly different factor level averages are denoted with an asterisk (\*). Comparisons complicated by interactions are denoted by a super-scripted letter with details given in a footnote

would have been lower after 8 months relative to 4 months; this is reflected in the higher anaerobic respiration volatile levels and the lower aerobic respiration levels observed in the 8 vs. 4 month fruit (Table 5). Furthermore, the ethylene levels of ULO fruit decreased with the longer duration, likely indicating that these fruit were post-climacteric in terms of maturity, while DCA fruit showed an increase in ethylene levels (Table 5), indicating that they were likely at an earlier maturity state and pre-climacteric.

The anaerobic respiration volatiles data showed that DCA greatly reduced the levels of anaerobic respiration volatiles relative to ULO in both year 1 and 2 of the study, while AVG greatly reduced the levels in year 2 of the study only (Tables 4 and 5). This could be due to the lower application rate or shorter preharvest interval in year 1, but it could also be the result of year differences. The finding that a lower oxygen level in storage produces fruit with lower levels of anaerobic respiration volatiles may at first

**Table 5** Year 2 post-controlled atmosphere (CA) storage pear headspace levels broken down by day (initial [Day 1] vs. shelf life [Day 4]), removal (4 vs. 8 month), field treatment (control vs. AVG) and storage treatment (ultra low oxygen [ULO] vs. dynamic controlled atmosphere [DCA]). AVG was applied 7 days before harvest in year 2

|                          | mL CO <sub>2</sub> (kg h) <sup>-1</sup> | Ethylene<br>μL C <sub>2</sub> H <sub>4</sub> (kg h) <sup>-1</sup> | Acetaldehyde<br>μL C <sub>2</sub> H <sub>4</sub> O (kg h) <sup>-1</sup> | Ethyl acetate<br>μL C <sub>4</sub> H <sub>8</sub> O <sub>2</sub> (kg h) <sup>-1</sup> | Ethanol<br>μL C <sub>2</sub> H <sub>6</sub> O (kg h) <sup>-1</sup> |
|--------------------------|-----------------------------------------|-------------------------------------------------------------------|-------------------------------------------------------------------------|---------------------------------------------------------------------------------------|--------------------------------------------------------------------|
| <b>Day</b>               |                                         |                                                                   |                                                                         |                                                                                       |                                                                    |
| Day 1 (initial)          | 8.1*                                    | 43.8*                                                             | 11.7*                                                                   | 6.3*                                                                                  | 40.2*                                                              |
| Day 4 (shelf)            | 17.0*                                   | 70.5*                                                             | 47.3*                                                                   | 30.2*                                                                                 | 325.5*                                                             |
| <b>Removal</b>           |                                         |                                                                   |                                                                         |                                                                                       |                                                                    |
| 4 month                  | 13.8 <sup>a</sup>                       | 55.1 <sup>c</sup>                                                 | 7.1*                                                                    | 3.9*                                                                                  | 19.0*                                                              |
| 8 month                  | 10.8 <sup>a</sup>                       | 58.0 <sup>c</sup>                                                 | 58.3*                                                                   | 39.1*                                                                                 | 445.6*                                                             |
| <b>Field treatment</b>   |                                         |                                                                   |                                                                         |                                                                                       |                                                                    |
| Control                  | 14.9*                                   | 85.7*                                                             | 37.5 <sup>d</sup>                                                       | 20.1*                                                                                 | 229.6*                                                             |
| AVG                      | 9.6*                                    | 28.3*                                                             | 17.5 <sup>d</sup>                                                       | 14.3*                                                                                 | 73.1*                                                              |
| <b>Storage treatment</b> |                                         |                                                                   |                                                                         |                                                                                       |                                                                    |
| ULO                      | 13.5 <sup>b</sup>                       | 63.8*                                                             | 31.7*                                                                   | 21.8*                                                                                 | 178.4*                                                             |
| DCA                      | 10.9 <sup>b</sup>                       | 48.5*                                                             | 21.9*                                                                   | 10.2*                                                                                 | 102.2*                                                             |

Significantly different factor level averages are denoted with an asterisk (\*). Comparisons complicated by interactions are denoted by a super-scripted letter with details given in a footnote

<sup>a</sup>Removal × Day < 0.001. No difference in CO<sub>2</sub> on day 1, but 4 month (20.3) > 8 month (13.8) for day 4 fruit

<sup>b</sup>Removal × Storage = 0.005. No difference in CO<sub>2</sub> at 8 months, but ULO (15.9) > DCA (11.6) at 4 months

<sup>c</sup>Removal × Field × Storage = 0.01. DCA control fruit showed an increase in C<sub>2</sub>H<sub>4</sub> with storage length: 8 month (90.3) < 4 month (67.1). ULO control fruit showed a decrease in C<sub>2</sub>H<sub>4</sub> with storage length: 8 month (102.9) < 4 month (83.3)

<sup>d</sup>Day × Field = 0.003. No difference in C<sub>2</sub>H<sub>4</sub>O on Day 1, but control (85.3) > AVG (36.5) on Day 4

seem counterintuitive; however, this finding most likely indicates that the levels of volatiles within the fruit depend on differences in maturity or general quality after a long storage period, and they are only indirectly related to the oxygen level in the storage cabinets. Multiple stressors, such as cold or warm temperatures, or chemicals such as ozone, have been shown to induce the production of anaerobic respiration volatiles in fruits and vegetables (Fan et al. 2008; Forney et al. 2000, 2007; Song et al. 2001). Furthermore, the production of these volatiles can simply be an indicator of poorer fruit quality and reflect differences in the fruit along their fruit maturity/senescence trajectories (Pott et al. 2020).

## Disorders

Other studies have reported a lower incidence of disorders with the use of AVG (Dong 2020; D'Aquino et al. 2010). Storage rot incidence was low after 4 months of CA storage in both years of the study; rots accounted for approximately 2% and 3% in year 1 and year 2, respectively. There was no correlation between rot incidence and field or storage treatment. After 8 months of storage, performed in year 2 only, rot incidence rose to approximately 5%; however, as in the case of 4 months, no correlation was found with either the field or storage treatments. It is possible that the use of ULO itself, compared to the use of standard CA or refrigerated air, which were not included in this study, was

sufficient to control most storage disorders across the study years and sites.

Pear “scuffing” (Fig. 1b), also referred to as “handling scald” (Eaves et al. 1969), over the course of the shelf life is an issue that was observed in year 2; only negligible levels were observed in year 1. Scuffing is not caused by, but can become more apparent during, storage and is even more common after storage. When pears are rubbed or scuffed during packing and sorting or other post-harvest activities, dark brown marks may appear on the pear skin, which contrasts with the yellow background and is unappealing. The browning is caused by cell damage and oxidative browning associated with polyphenol oxidase. The conditions that prevail during the growing season, at harvest and during storage also influence the susceptibility of pears to scuffing damage. The scuffing levels for the ULO, ULO + AVG, DCA and DCA + AVG treatments averaged over both the 4-month and 8-month removals in year 2 were 65%, 60%, 35% and 10%, respectively. Scuffing levels were approximately 10% higher after 8 months than after 4 months. Initial maturity (measured as firmness) among the four growers was negatively correlated with the scuffing level. Initial grower firmness levels found at sites 1 through 4 were 88.6, 82.3, 82.3, 89.0 N and corresponded to scuffing incidence levels of 25%, 55%, 53% and 38%, respectively. Sites with harvest firmness levels < 85 N had higher scuffing, and fruit > 85 N firmness had lower scuffing. Pears typically become more vulnerable to scuffing damage as they soften and mature. While year 1 fruit were not firmer than year 2

fruit at harvest (Table 1), growing conditions differed between the 2 years. The fruit in year 1 were smaller than in year 2 and this may also have been a factor. The reduced yellowing and improved firmness retention of DCA + AVG treatment, relative to all others, likely explains the reduced scuffing incidence. This finding is an agreement with an early report by Eaves et al. (1969) that showed flushing stores with nitrogen also reduced scuffing incidence.

### Anti-ethylene Modes of Action

Previous studies have shown that pear maturity can be further delayed in storage or that the incidence of disorders can be reduced through ethylene inhibition strategies such as DCA (Prange et al. 2011; Deuchande et al. 2016) or AVG (Ness and Romani 1980; Clayton et al. 2000; Andreotti et al. 2004). The present study presents evidence of an additive effect from the combined use of DCA and AVG as compared to either treatment used on its own (Tables 2, 3, 4 and 5). Both strategies inhibit the endogenous production of ethylene within the fruit; however, each strategy impacts the ethylene biosynthesis pathway in a different location. Limiting oxygen availability—which would be more pronounced with DCA than with ULO or standard CA—inhibits the activity of ACC oxidase and the conversion of ACC into ethylene. As might be expected, the use of low oxygen to retard ethylene synthesis has been linked to a buildup of ACC (Zhen-guo et al. 1983). This buildup of ACC effectively primes the fruit for ethylene production once the fruit is reintroduced to normoxic conditions. AVG acts on an earlier stage of the ethylene pathway and inhibits the action of ACC synthase, thereby limiting the production of the ethylene precursor ACC (Venburg et al. 2008). This dual approach is associated with the greatest reduction in ethylene in both years of the study (Tables 4 and 5). The additive benefit of this combined approach for pear storage is in agreement with the limited examples found in the literature. Dong (2020) showed that a combined approach was the best for limiting superficial scald in 'd'Anjou' pears. Similarly, combining DCA with AVG in apples was found to greatly improve storage outcomes relative to either approach used separately (Wendt et al. 2022).

The anti-ethylene product 1-methylcyclopropene (1-MCP) inhibits ethylene action by blocking ethylene receptor sites. The product is highly effective at slowing maturity and inhibits the action of both endogenous and exogenous sources. However, the need for pear fruit to turn yellow rapidly and soften after storage makes it more difficult to strike a balance between the timing and dosage of 1-MCP in order to delay maturity in storage but still allow for the rapid maturation of fruit post-storage. Like 1-MCP, AVG reduces the action of endogenous ethylene on climacteric fruit maturation; however, unlike 1-MCP,

AVG remains vulnerable to exogenous sources of ethylene as a result of its mode of action. Fruit treated with AVG showed a reduced rate of yellowing and softening in this trial despite the AVG fruit being stored in the same cabinet as untreated control fruit. Exogenous ethylene from the untreated control fruit may have hastened ripening in the treated AVG fruit. It is possible that the efficacy of AVG use in the treated fruit might have been greater in this study, had the untreated control and the AVG treated fruit been stored in separate cabinets.

### Conclusions

The combined use of AVG applied preharvest and low oxygen storage using DCA slowed fruit maturation during and after storage to a greater extent than did either treatment used on its own. Delayed fruit maturation was primarily expressed as a reduced rate of yellowing and lower levels of ethylene, respiration and anaerobic respiration volatiles. Lower anaerobic respiration volatile levels reflected higher fruit quality. Fruit that received the combined DCA + AVG treatment had the lowest incidence of pear scuffing, while untreated fruit stored under ULO showed the highest incidence. An acceptable level of fruit softening post storage was not a concern with any treatment combination; however, fruit de-greening was a concern, most notably in fruit harvested at a firmness level above the recommended 85 N under the combined DCA + AVG treatment.

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### Declarations

**Conflict of interest** A. H. Wright declares that he has no competing interests. R.K. Prange was a member of the team that developed and patented the technology behind the HarvestWatch™ system, a fluorescence-based form of dynamic controlled atmosphere (DCA) (Prange et al. 2002).

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## References

- Andreotti C, Bregoli AM, Costa G (2004) Pre- and post-harvest Aminoethoxyvinylglycine (AVG) application affects maturity and storage of pear fruit. *Eur J Hort Sci* 69:147–152
- Batur S, Çetinbaş M (2017) Pre-harvest application of reTain (Aminoethoxyvinylglycine, AVG) influences pre-harvest drop and fruit quality of 'williams' pears. *Tarim Bilim Derg.* <https://doi.org/10.15832/ankutbd.447704>
- Clayton M, Biasi WV, Southwick SM, Mitcham EJ (2000) ReTain™ affects maturity and ripening of 'Bartlett' pear. *HortScience* 35(7):1294–1299. <https://doi.org/10.21273/hortsci.35.7.1294>
- Curry EA (2008) Regulating ripening of 'bartlett' pears using pre-harvest plus postharvest Aminoethoxyvinylglycine (AVG). *Open Hortic J* 1:21–25
- D'Aquino S, Schirra M, Molinu MG, Tedde M, Palma A (2010) Preharvest aminoethoxyvinylglycine treatments reduce internal browning and prolong the shelf-life of early ripening pears. *Sci Hortic* 125(3):353–360. <https://doi.org/10.1016/j.scienta.2010.04.020>
- DeLong, JM, Prange, RK, Leyte, JC, Harrison, PA, (2004). A new technology that determines low-oxygen thresholds in controlled-atmosphere-stored apples. *Hort Technol* 14(2):262–266. <https://doi.org/10.21273/horttech.14.2.0262>
- Deuchande T, Carvalho SMP, Guterres U, Fidalgo F, Isidoro N, Larri-gaudière C, Vasconcelos MW (2016) Dynamic controlled atmosphere for prevention of internal browning disorders in 'Rocha' pear. *LWT* 65:725–730. <https://doi.org/10.1016/j.lwt.2015.08.075>
- Dong Y (2020) Mechanisms and practical solutions to control scald in pears. Washington Tree Fruit Research Commission. <https://treefruitresearch.org/report/mechanisms-and-practical-solutions-to-control-scald-of-pears/>. Accessed 27 Mar 2021
- Dussi MC, Sosa D, Calvo GS (2002) Effects of ReTain on fruit maturity and fruit set on pear cultivars williams and Packham triumph. *International Society for Horticultural Science (ISHS), Leuven*, pp 767–771 <https://doi.org/10.17660/ActaHortic.2002.596.132>
- Eaves CA, Forsyth FR, Lockhart CL (1969) Recent developments in storage research at Kentville, Nova Scotia. *Can Inst Food Technol J* 2(1):46–51. [https://doi.org/10.1016/S0008-3860\(69\)74342-2](https://doi.org/10.1016/S0008-3860(69)74342-2)
- Emre M, Butar S, Cetinbas M, Emre RA (2019) Economic evaluation of aminoethoxyvinylglycine (AVG) applications in 'Williams' pear cultivar. *International Society for Horticultural Science (ISHS), Leuven*, pp 87–92 <https://doi.org/10.17660/ActaHortic.2019.1258.12>
- Environment and Climate Change Canada (2022) Kentville weather data. [https://climate.weather.gc.ca/climate\\_data/daily\\_data\\_e.html?StationID=27141](https://climate.weather.gc.ca/climate_data/daily_data_e.html?StationID=27141). Accessed 1 Dec 2022
- Fan L, Forney CF, Song J, Doucette C, Jordan MA, McRae KB, Walker BA (2008) Effect of hot water treatments on quality of highbush blueberries. *J Food Sci* 73(6):M292–M297. <https://doi.org/10.1111/j.1750-3841.2008.00838.x>
- Forney CF, Jordan MA, Nicholas KUKG (2000) Volatile emissions and chlorophyll fluorescence as indicators of freezing injury in apple fruit. *HortScience* 35(7):1283–1287. <https://doi.org/10.21273/hortsci.35.7.1283>
- Forney CF, Song J, Hildebrand PD, Fan L, McRae KB (2007) Interactive effects of ozone and 1-methylcyclopropene on decay resistance and quality of stored carrots. *Postharvest Biol Technol* 45(3):341–348. <https://doi.org/10.1016/j.postharvbio.2007.03.006>
- Kupferman E (2003) Controlled atmosphere storage of apples and pears. *International Society for Horticultural Science (ISHS), Leuven*, pp 729–735 <https://doi.org/10.17660/ActaHortic.2003.600.111>
- Lara I, Heredia A, Domínguez E (2019) Shelf life potential and the fruit cuticle: the unexpected player. *Front Plant Sci.* <https://doi.org/10.3389/fpls.2019.00770>
- Mitcham EJ, Crisosto CH, Kader AA (1996) Pear (Bartlett) Recommendations for Maintaining Postharvest Quality, Perishables Handling #86. UC Davis, Davis, California, p 4
- Ness PJ, Romani RJ (1980) Effects of aminoethoxyvinylglycine and countereffects of ethylene on ripening of bartlett pear fruits. *Plant Physiol* 65(2):372–376. <https://doi.org/10.1104/pp.65.2.372>
- Porritt SW (1965) Effect of cooling rate on storage life of pears *Can J Plant Sci* 45:8
- Pott DM, de Abreu e Lima F, Soria C, Willmitzer L, Fernie AR, Nikoloski Z, Osorio S, Vallarino JG (2020) Metabolic reconfiguration of strawberry physiology in response to postharvest practices. *Food Chem* 321:126747. <https://doi.org/10.1016/j.foodchem.2020.126747>
- Prange RK (2022) Controlled atmosphere storage of apples and pears. Prange Publications, Wolfville, Nova Scotia, Canada
- Prange R, DeLong J, Harrison P, Leyte J, Mclean S, Scrutton J, Cullen J (2002) Method and apparatus for monitoring a condition in chlorophyll containing matter. *Canada Patent*, 24.01.2002
- Prange RK, DeLong JM, Wright AH (2011) Storage of pears using dynamic controlled-atmosphere (DCA), a non-chemical method. *Acta Hortic* 909:707. <https://doi.org/10.17660/ActaHortic.2011.909.87>
- R Development Core Team (2022) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
- Romani R, Puschmann R, Finch J, Beutel J (1982) Effects of preharvest applications of AVG on ripening of 'Bartlett' pears with and without cold storage. *HortScience* 17:214–215
- Song J, Fan L, Forney CF, Jordan MA (2001) Using volatile emissions and chlorophyll fluorescence as indicators of heat injury in apples. *J Am Soc Hortic Sci* 126(6):771–777. <https://doi.org/10.21273/jashs.126.6.771>
- Venbun GD, Hopkins R, Retamales J, Lopez J, Hansen J, Clarke GG, Schröder M, Rath AC (2008) Recent developments in AVG research (trans: Cost). *International Conference on Ripening Regulation and Postharvest Fruit Quality*. vol 796. *International Society for Horticultural Science, Weingarten* <https://doi.org/10.17660/ActaHortic.2008.796.3>
- Wang Y, Xie X, Song J (2016) Preharvest aminoethoxyvinylglycine spray efficacy in improving storability of 'Bartlett' pears is affected by application rate, timing, and fruit harvest maturity. *Postharvest Biol Technol* 119:69–76. <https://doi.org/10.1016/j.postharvbio.2016.04.023>
- Wendt LM, Soldateli FJ, Both V, Thewes FR, Ludwig V, Berghetti MRP, dos Santos Ferrão T, Wagner R, Brackmann A (2022) Effects of ethylene control and dynamic controlled atmosphere storage on 'galaxy' apple quality. *J Plant Growth Regul.* <https://doi.org/10.1007/s00344-022-10578-5>
- Wright AH, DeLong JM, Gunawardena AHLAN, Prange RK (2012) Dynamic controlled atmosphere (DCA): does fluorescence reflect physiology in storage? *Postharvest Biol Technol* 64(1):19–30. <https://doi.org/10.1016/j.postharvbio.2011.09.015>

Zhen-guo L, Yu L, Jian-guo D, Rong-jiang X, Mei-zhen Z (1983) Effect of low oxygen and high carbon dioxide on the levels of ethylene and 1-aminocyclopropane-1-carboxylic acid in ripening apple fruits. *J Plant Growth Regul* 2(1):81–87. <https://doi.org/10.1007/BF02042236>

Data can be made available upon reasonable request.