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# Effects of Preharvest and Postharvest Applications of 1-Methylcyclopropene on Fruit Quality and Physiological Disorders of 'Fuji' Apples during Storage at Warm and Cold Temperatures

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***Abstract.*** **The effects of preharvest and postharvest treatments of 1-methylcyclopropene (1-MCP) in combination or alone on fruit quality and the incidence of physiological disorders during storage of 'Fuji' apples [*Malus sylvestris* (L.) Mill var. *domestica* (Borkh.) Mansf.] at 20 and 0.5 °C were investigated. Preharvest 1-MCP (Harvista) treatments were applied 4 or 10 days before harvest (DBH), and then fruit were either untreated or treated with 1-MCP (SmartFresh) postharvest. Fruit were stored at 20 °C for up to 4 weeks or at 0.5 °C for up to 36 weeks. At harvest, starch pattern indices and watercore incidence and severity were lower in fruit with preharvest 1-MCP treatment applied 10 DBH than in untreated fruit and in fruit treated 4 DBH. At 20 °C, the combination of preharvest and postharvest 1-MCP treatments reduced the internal ethylene concentration (IEC) more than preharvest 1-MCP treatment alone, but not to a greater extent than postharvest 1-MCP treatment alone. Greasiness and watercore were reduced more by the combination of preharvest and postharvest 1-MCP treatments than by either treatment alone. However, preharvest and postharvest 1-MCP treatments, in combination or alone, did not consistently affect flesh firmness, titratable acidity (TA), soluble solids concentration, color *a** values, or incidences of flesh browning, core browning, and stem-end flesh browning. At 0.5 °C, the combination of preharvest and postharvest 1-MCP treatments inhibited IECs and maintained firmness and TA more than no treatment or preharvest 1-MCP treatment alone. However, there was a lesser extent of differences than there was with postharvest 1-MCP treatment alone. Incidences of physiological disorders were not consistently affected by the preharvest and postharvest 1-MCP treatments. Overall, the results suggested that the preharvest 1-MCP treatment positively affected fruit quality attributes compared with no treatment during shelf life and long-term cold storage, but not as effectively as a combination of preharvest and postharvest 1-MCP treatments.**

Application of 1-MCP, an inhibitor of ethylene perception, is widely used by apple industries after harvest to maintain fruit quality attributes, such as fruit firmness, acidity, sweetness, juiciness, and crispiness (Bai et al., 2005; DeEll et al., 2007; DeLong et al., 2004; Larrigaudière et al., 2008; Jung and Lee, 2009; Watkins et al., 2000). Treatment with 1-MCP can reduce the development of certain physiological disorders, such as senescent breakdown (DeLong et al., 2004; Jung and Watkins, 2008), diffuse flesh breakdown (Lee et al., 2016), core browning (DeEll and Ehsani-Moghaddam, 2013), fruit cracking (Lee et al., 2016), flesh breakdown (Lee et al., 2013), peel greasiness (Dong et al., 2012), and superficial scald (Lurie and Watkins, 2012). However, 1-MCP can increase the incidence of diffuse skin browning (Larrigaudière et al., 2010), flesh browning (Lee et al., 2012; Watkins, 2008), radial stem-end flesh breakdown (Lee et al., 2016), and $CO_2$ injury (DeEll et al., 2003; Fawbush et al., 2008; Zanella, 2003).

A preharvest 1-MCP spray formulation (Harvista) is available commercially in North America and other regions. Preharvest 1-MCP treatment reduces fruit drop for 'McIntosh', 'Delicious', 'Golden Delicious', and 'Bisbee Delicious' apples (McArtney et al., 2008; Yuan and Li, 2008; Watkins et al., 2010). In addition, preharvest treatment can retain fruit firmness of 'Gamhong' apples during cold storage (Yoo et al., 2013) and of 'Delicious' apples during long-term controlled atmosphere (CA) storage (Elfving et al., 2007). Preharvest 1-MCP treatment did not affect flesh firmness and starch pattern index values (SPIs) of 'Law Rome' apples (McArtney et al., 2009), but it did reduce internal ethylene concentrations (IECs), chlorophyll content (in terms of $I_{AD}$ values), and starch hydrolysis of 'Gala' apples (Doerflinger et al., 2015a). Preharvest 1-MCP applications reduced the incidences of soft scald and soggy breakdown in 'Honeycrisp' apple (DeEll and Ehsani-Moghaddam, 2010) and superficial scald in 'Golden Delicious' apple (McArtney et al., 2008). Preharvest 1-MCP treatment had few effects on the watercore development of 'Delicious' apple (Elfving et al., 2007), but it delayed it in another study (Yuan and Li, 2008). Fruit quality attributes at harvest are less consistently affected by preharvest 1-MCP (Elfving et al., 2007; McArtney et al., 2008; Yuan and Carbaugh, 2007; Yuan and Li, 2008; Watkins et al., 2010) than by postharvest 1-MCP treatment (Kim et al., 2018; Lu et al., 2013; Watkins and Nock, 2012). Varanasi et al. (2013) reported that preharvest 1-MCP treatment alone was relatively less effective for IEC, fruit firmness, and SPI than the combined application of preharvest and postharvest 1-MCP treatments. Overall, limited studies have reported the combined effects of preharvest and postharvest treatments on fruit quality during cold storage, and none has reported the effects on fruit quality during warm (20 °C) conditions that might occur in some international markets.

The objective of this study was to evaluate the effectiveness of preharvest and postharvest 1-MCP applications, in combination or alone, on fruit quality and the incidence of physiological disorders for 'Fuji' apple fruit during extended periods of 4 weeks at 20 °C and after long-term cold storage at 0.5 °C. 'Fuji' apples have distinctive fruit quality attributes in terms of fruit texture (Costa et al., 2012). However, fruit of the cultivar are highly susceptible to the development of watercore at harvest (Bowen and Watkins, 1997; Kweon et al., 2013) and the development of flesh browning, core browning, brown heart, and $CO_2$ injury during storage (Argenta et al., 2000, 2002; Kweon et al., 2012, 2013).

## Materials and Methods

*Fruit source, treatments, and shelf life and storage conditions.* 'Fuji' apple [*Malus*

Table 1. Values of the internal ethylene concentration (IEC), flesh firmness, titratable acidity (TA), soluble solids concentration (SSC), starch pattern index (SPI), *a** values, and watercore incidence and severity of 'Fuji' apples untreated or treated with preharvest 1-MCP (Harvista) at 4 or 10 d before harvest (DBH) at harvest.

| Harvista (DBH) | Log IEC ($\mu L \cdot L^{-1}$) | Firmness (N) | TA (%) | SSC (%) | Starch pattern index (1–8) | *a** | Watercore incidence (%) | Watercore severity (0–3) |
|---|---|---|---|---|---|---|---|---|
| – | 0.17 a[z] | 66.2 b | 0.350 a | 12.7 a | 7.8 a | 28.91 a | 85 a | 1.4 a |
| 4 | 0.19 a | 67.8 a | 0.333 a | 12.7 a | 7.7 a | 29.94 a | 80 a | 1.5 a |
| 10 | 0.06 a | 66.6 ab | 0.326 a | 12.4 a | 7.5 b | 30.04 a | 55 b | 0.7 b |

[z]Means in each category followed by the same letters do not differ significantly. Duncan's multiple range test, $P = 0.05$.

Table 2. Internal ethylene concentration (IEC), flesh firmness, titratable acidity (TA), soluble solids concentration (SSC), and *a** values of 'Fuji' apples stored at 20 °C for up to 4 weeks.[z]

| Storage time (wk) | Harvista treatment (DBH) | Log IEC ($\mu L \cdot L^{-1}$) | | Firmness (N) | | TA (%) | | SSC (%) | | *a** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | – | + | – | + | – | + | – | + | – | + |
| 0 | – | 0.2 | | 66.2 | | 0.350 | | 12.7 | | 28.9 | |
| | 4 | 0.2 | | 67.8 | | 0.333 | | 12.7 | | 29.9 | |
| | 10 | 0.1 | | 66.6 | | 0.326 | | 12.4 | | 30.0 | |
| 1 | – | 1.8 | 0.0 | 69.2 | 69.4 | 0.305 | 0.320 | 12.6 | 12.8 | 28.8 | 30.7 |
| | 4 | 0.9 | 0.1 | 70.2 | 70.7 | 0.310 | 0.325 | 12.4 | 12.7 | 29.6 | 31.0 |
| | 10 | 0.3 | 0.1 | 70.0 | 70.3 | 0.321 | 0.321 | 12.7 | 12.4 | 29.2 | 29.7 |
| 2 | – | 2.1 | 0.1 | 66.3 | 70.6 | 0.256 | 0.295 | 12.9 | 13.0 | 28.6 | 29.8 |
| | 4 | 1.4 | 0.2 | 71.8 | 70.9 | 0.295 | 0.298 | 12.8 | 13.1 | 29.6 | 30.6 |
| | 10 | 0.9 | 0.2 | 71.2 | 71.0 | 0.301 | 0.308 | 13.0 | 12.8 | 29.5 | 29.1 |
| 3 | – | 2.3 | 0.3 | 67.3 | 69.3 | 0.238 | 0.293 | 12.3 | 13.0 | 27.4 | 29.3 |
| | 4 | 1.6 | 0.2 | 70.7 | 70.3 | 0.283 | 0.276 | 12.8 | 12.9 | 28.9 | 29.5 |
| | 10 | 1.1 | 0.4 | 70.5 | 71.8 | 0.290 | 0.295 | 12.3 | 12.8 | 28.9 | 29.9 |
| 4 | – | 2.4 | 0.4 | 67.0 | 70.3 | 0.213 | 0.286 | 12.5 | 13.2 | 29.6 | 30.3 |
| | 4 | 1.8 | 0.2 | 70.6 | 70.7 | 0.261 | 0.276 | 12.8 | 13.1 | 29.0 | 30.0 |
| | 10 | 1.6 | 0.5 | 71.5 | 73.0 | 0.274 | 0.291 | 12.8 | 12.9 | 29.0 | 30.9 |
| | $LSD_{0.05}$ | 0.26 | | 2.24 | | 0.0188 | | 0.70 | | 2.25 | |
| Significance | | | | | | | | | | | |
| Storage time (T) | | **<0.0001** | | **<0.0001** | | **<0.0001** | | 0.1926 | | 0.2115 | |
| Harvista (H) | | **<0.0001** | | **<0.0001** | | **0.0215** | | 0.4492 | | 0.4011 | |
| SmartFresh (S) | | **<0.0001** | | **0.0027** | | **<0.0001** | | **0.0200** | | **0.0021** | |
| T×H | | **<0.0001** | | 0.1142 | | **0.0247** | | 0.9248 | | 0.8532 | |
| T×S | | **<0.0001** | | 0.5662 | | 0.2664 | | 0.3926 | | 0.8882 | |
| H×S | | **<0.0001** | | **0.0054** | | **0.0005** | | 0.2297 | | 0.6848 | |
| T×H×S | | **<0.0001** | | 0.2711 | | 0.4853 | | 0.7776 | | 0.8842 | |

[z]Fruit were untreated or treated with preharvest 1-MCP (Harvista) at 4 or 10 d before harvest (DBH) and untreated (–) or treated (+) with postharvest 1-MCP.

*sylvestris* (L.) Mill var. *domestica* (Borkh.) Mansf.] fruit used for this experiment were harvested from mature trees growing at the Cornell University Research Orchard located in Lansing, NY. Twelve replicates of five trees per treatment were marked and four replicates were randomly assigned to each of three treatments: untreated or preharvest 1-MCP treatment at 4 or 10 DBH.

Preharvest 1-MCP was prepared by mixing 1-MCP (AFxRD-038; AgroFresh Inc., Dow AgroSciences, Spring House, PA) and sprayed at a product rate of 12.6 $kg \cdot ha^{-1}$. The mixing and application procedures were described by McArtney et al. (2008), except no oil was used. Each spray treatment was applied immediately after mixing using a $CO_2$ pressure sprayer (Bellspray, Opelousas, LA) calibrated to deliver the spray at 276 kPa and fitted with a TeeJet 8004VS flat fan nozzle (Spraying Systems, Wheaton, IL).

On 20 Oct. 2010, 600 fruit were harvested from each replicate per treatment; of those 600 fruit, 200 were kept at 20 °C and 400 were kept at 0.5 °C overnight. Half of the fruit of each replicate were then untreated or treated with 1 $\mu L \cdot L^{-1}$ 1-MCP for 24 h at the respective temperatures using SmartFresh tablets (0.36% a.i., AgroFresh Inc., Dow AgroSciences) in a 4000-L plastic tent using a release and fan system supplied by the manufacturers.

Untreated or treated fruit were stored at either 20 °C for 4 weeks or 0.5 °C for 36 weeks. Ten fruit per replicate of the six treatments (three field treatments with or without 1-MCP) were taken at random for the evaluation of fruit quality attributes at 1-week intervals and at 6-week intervals, respectively. The cold-stored fruit were evaluated after 1 d at 20 °C.

*Measurement of harvest indices.* The IEC of each fruit was measured using 1-mL samples of internal gas from the core cavity using a Hewlett-Packard 5890 series II gas chromatograph (Hewlett-Packard, Wilmington, DE) equipped with a flame ionization detector and fitted with a stainless-steel column packed with 60/80 mesh alumina F-1 (2 m × 2 mm i.d.). Analyses were performed isothermally with an oven temperature of 200 °C and injector and detector temperatures of 220 and 250 °C, respectively. The flow rates of nitrogen, hydrogen, and compressed air were 30, 30, and 230 $mL \cdot min^{-1}$. Ethylene was quantified by the peak area, and an external standard of 10 $\mu L \cdot L^{-1}$ was used for calibration.

Peel color, as the *a** value (+ = redder, – = greener), was measured on fruit peel tissue at three locations at the equatorial region with a chromameter (Minolta CR-300; Minolta Co., Osaka, Japan). Flesh firmness was measured on opposite peeled sides using a fruit texture analyzer (Guss Manufacturing Pty. Ltd., Strand, South Africa) fitted with an 11.1-mm-diameter probe. The expressed juice was used for soluble solids concentration (SSC) measurements with a refractometer (PR-100; Atago Co. Ltd., Tokyo, Japan). The TA was measured using 1 mL of juice and 0.1 N NaOH to an endpoint of pH 8.1 with an autotitrator (Mettler DL12; Mettler, Hightstown, NJ) and expressed as the percentage of malic acid. The SPI was determined according to Blanpied and Silsby (1992), where 1 = 100% staining and 8 = 0% starch.

*Physiological disorders.* The incidence and severity of greasiness, determined subjectively by touch, and any external symptoms,

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Table 3. Greasiness incidence, watercore incidence and severity, and incidences of flesh browning, core browning and stem-end browning of 'Fuji' apples stored at 20 °C for up to 4 weeks.[z]

| Storage time (wk) | Harvista treatment (DBH) | Greasiness (%) | | Watercore incidence (%) | | Watercore severity (0–3) | | Flesh browning (%) | | Core browning (%) | | Stem-end browning (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | – | + | – | + | – | + | – | + | – | + | – | + |
| 0 | – | 0[c] | | 85 | | 1.4 | | 0 | | 0 | | 0 | |
| | 4 | 0 | | 80 | | 1.5 | | 0 | | 0 | | 0 | |
| | 10 | 0 | | 55 | | 0.7 | | 0 | | 0 | | 0 | |
| 1 | – | 55 | 30 | 58 | 38 | 0.7 | 0.6 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4 | 18 | 5 | 28 | 23 | 0.2 | 0.4 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 10 | 8 | 0 | 3 | 0 | 0.0 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | – | 68 | 25 | 8 | 3 | 0.1 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4 | 13 | 23 | 10 | 3 | 0.1 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 10 | 18 | 18 | 5 | 0 | 0.1 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | – | 100 | 5 | 0 | 3 | 0.0 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4 | 30 | 5 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 10 | 13 | 3 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | – | 100 | 38 | 0 | 0 | 0.0 | 0.0 | 0 | 3 | 0 | 18 | 0 | 13 |
| | 4 | 72 | 10 | 0 | 0 | 0.0 | 0.0 | 3 | 8 | 0 | 7 | 0 | 30 |
| | 10 | 53 | 15 | 0 | 0 | 0.0 | 0.0 | 5 | 13 | 3 | 5 | 0 | 0 |
| | $LSD_{0.05}$ | 18.8 | | 17.7 | | 0.3 | | 4.4 | | 5.6 | | 4.1 | |
| Significance | | | | | | | | | | | | | |
| Storage time (T) | | **<0.0001** | | **<0.0001** | | **<0.0001** | | **<0.0001** | | **<0.0001** | | **<0.0001** | |
| Harvista (H) | | **<0.0001** | | **<0.0001** | | **<0.0001** | | 0.0926 | | 0.3337 | | 0.3864 | |
| SmartFresh (S) | | **<0.0001** | | 0.5453 | | 0.1709 | | 0.0548 | | **0.0068** | | 0.1467 | |
| T×H | | **<0.0001** | | **<0.0001** | | **<0.0001** | | **0.0386** | | 0.6296 | | 0.3778 | |
| T×S | | **<0.0001** | | 0.9040 | | 0.4604 | | **0.0133** | | **0.0001** | | 0.1006 | |
| H×S | | **<0.0001** | | 0.8928 | | 0.8315 | | 0.7297 | | 0.1747 | | **0.0097** | |
| T×H×S | | **0.0012** | | 0.9774 | | 0.9167 | | 0.9267 | | 0.1129 | | **0.0003** | |

[z]Fruit were untreated or treated with preharvest 1-MCP (Harvista) at 4 or 10 d before harvest (DBH) and untreated (–) or treated (+) with postharvest 1-MCP.

such as shrivel and decay, were assessed. Then, the fruit were sliced horizontally at least three times to assess the incidence of any internal physiological disorders. These included watercore, flesh browning, core browning, and stem-end flesh browning. The watercore severity rating was subjectively evaluated: 0 = no watercore; 1 = slight watercore; 2 = moderate watercore; and 3 = severe watercore.

*Statistical analyses.* Duncan's multiple range test was used to compare the means of the harvest data at $P = 0.05$. Shelf life and storage data sets were subjected to a two-way analysis of variance using the general linear model (Proc GLM) to determine main effects and interactions (version 9.3; SAS Institute Inc., Cary, NC). IEC data were transformed to logarithms before the statistical analysis and shown as transformed means for data presentation. An analysis of Pearson correlations was performed using SAS. Red and blue colors represent positive and negative correlations between factors, respectively (*, **, ***, or **** indicate significant correlations at $P < 0.05$, 0.01, 0.001, or 0.0001, respectively).

All physiological and disorder data were analyzed using a partial least-squares (PLS) regression analysis as described by Lee et al. (2012). PLS relates variations of a limited number of predictor variables (Y-variables) to the variations of a large number of predictor variables (X-variables). PLS is a regression analysis technique that involves the original X-data being projected onto a small number of underlying latent variables (LVs) that are concurrently used for regression of the Y-data in such a way that the first LVs are most relevant for predicting the Y-variables. Fruit quality data were considered predictor variables, whereas treatment factors (untreated or treated with Harvista and/or SmartFresh) and storage time (0–4 weeks at 20 °C and 0–36 weeks at 0.5 °C) were considered response variables. The treatment factors were introduced as separate categorical variables (reading either –1 or 1), whereas storage time was considered a continuous variable. Both X-data and Y-data were transformed by using mean-centered and standard deviation scaled-to-unit variance to give all variables an equal chance to influence the

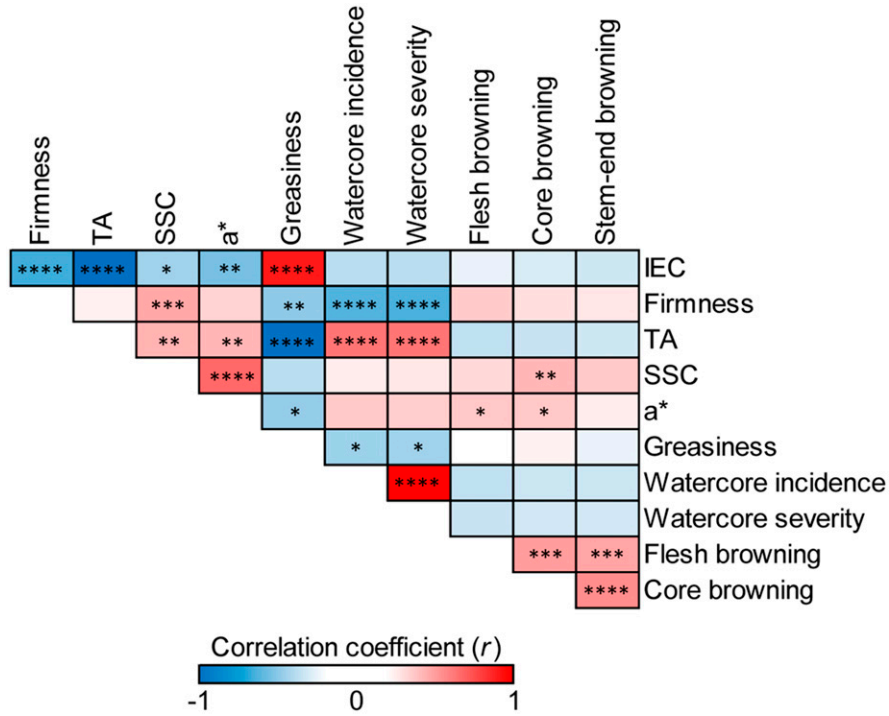


Fig. 1. Pearson correlation coefficient ($r$) matrix for fruit quality attributes and the incidence of physiological disorders with preharvest and postharvest 1-MCP treatments in combination or alone in 'Fuji' apples for up to 4 weeks at 20 °C. IEC, internal ethylene concentration; TA, titratable acidity; SSC, soluble solids concentration. Red and blue colors represent positive and negative correlation between factors. *, **, ***, or **** indicate statistically significant correlations at $P < 0.05$, 0.01, 0.001, or 0.0001, respectively.

model. The PLS regression analysis was performed using The Unscrambler version 10.0.1 (Camo Software Inc., Woodbridge, NJ).

## Results

*Harvest.* The IEC, TA, SSC, and *a** values were unaffected by preharvest treatment (Table 1). Flesh firmness was higher for 1-MCP–treated fruit than for untreated fruit, although the firmness of fruit treated 10 DBH was intermediate compared to untreated fruit and fruit treated 4 DBH. The SPI and watercore incidence and severity were lower for fruit treated 10 DBH than for untreated fruit and fruit treated 4 DBH.

*Storage at 20 °C.* IEC was affected by storage time, preharvest 1-MCP treatment, and postharvest 1-MCP treatment (Table 2). The IEC of untreated fruit increased rapidly after 1 week at 20 °C, and then it increased only slightly over time. Preharvest 1-MCP treatment delayed the increase in IEC and, to a greater extent, in those treated 10 DBH than 4 DBH. At 4 weeks at 20 °C, differences between the two 1-MCP treatments were small. Postharvest 1-MCP inhibited the increase of IEC in both untreated fruit and preharvest 1-MCP–treated fruit.

Flesh firmness was affected by storage time, preharvest 1-MCP treatment, and postharvest 1-MCP treatment (Table 2). Flesh firmness did not change greatly between weeks 1 and 4, but it was higher for fruit with preharvest 1-MCP treatments than for the untreated controls. TA was also affected by an interaction between preharvest and postharvest 1-MCP treatments and the interaction between treatment duration and preharvest 1-MCP treatment. SSC and *a** values were only affected by postharvest 1-MCP treatment. Overall, the SSC was 12.8% for postharvest 1-MCP–treated fruit compared with 12.4% for the control fruit, whereas the *a** values were 30.0 units for 1-MCP–treated fruit and 29.1 units for the control fruit. The *a** values were unaffected by storage duration or preharvest 1-MCP treatment, but they were affected by postharvest 1-MCP treatment.

Treatment effects on greasiness were variable and had the highest interactions (Table 3). Overall, greasiness development at 20 °C was lower in fruit treated with 1-MCP, both preharvest and postharvest. Postharvest 1-MCP had more consistent effects on greasiness when both preharvest and postharvest treatments were applied compared to only postharvest treatment. The incidence and severity of watercore decreased over time but interacted with the effects of the duration of preharvest 1-MCP treatment (Table 3). Postharvest 1-MCP treatment did not affect the incidence and severity of watercore during storage. Flesh browning, core browning, and stem-end browning were only detected at week 4. The incidence of flesh browning increased with increasing DBH and was higher in fruit treated with postharvest 1-MCP compared to those without 1-MCP treatment. Core browning was usually higher in fruit treated with postharvest 1-MCP than in those without, and especially in fruit without preharvest 1-MCP treatment. Stem-end flesh browning was only detected at week 4 and in untreated fruit and fruit with preharvest 1-MCP treatment 4 DBH that were also treated with postharvest 1-MCP.

The Pearson correlation coefficient test detected strong positive and negative correlations among fruit quality attributes and fruit physiological disorders during storage at 20 °C (Fig. 1). IEC was negatively correlated with firmness, TA, SSC, and *a**, but it was positively correlated with greasiness. Firmness was negatively correlated with greasiness and watercore, but it was positively correlated with SSC. TA was negatively correlated with greasiness, but it was positively correlated with SSC, *a**, and watercore incidence and severity. The SSC was positively correlated with *a** and core browning. The *a** value was negatively correlated with greasiness, but it was positively correlated with flesh browning and core browning. Greasiness was negatively correlated with watercore, but it was positively correlated with IEC. Watercore incidence and severity were positively correlated with each other. Flesh browning, core browning, and stem-end flesh browning were positively correlated with each other.

The PLS scores plot (Fig. 2A) indicated that fruit physiological responses diverged more with storage time and postharvest 1-MCP treatment than with preharvest 1-MCP treatment. However, when considering preharvest 1-MCP–treated fruit alone, the physiological responses of untreated fruit were distinctly separate from those of preharvest 1-MCP–treated fruit. This result suggested that fruit quality could be sustained to a greater extent by a combination of preharvest and postharvest 1-MCP treatments than by preharvest 1-MCP treatment alone.

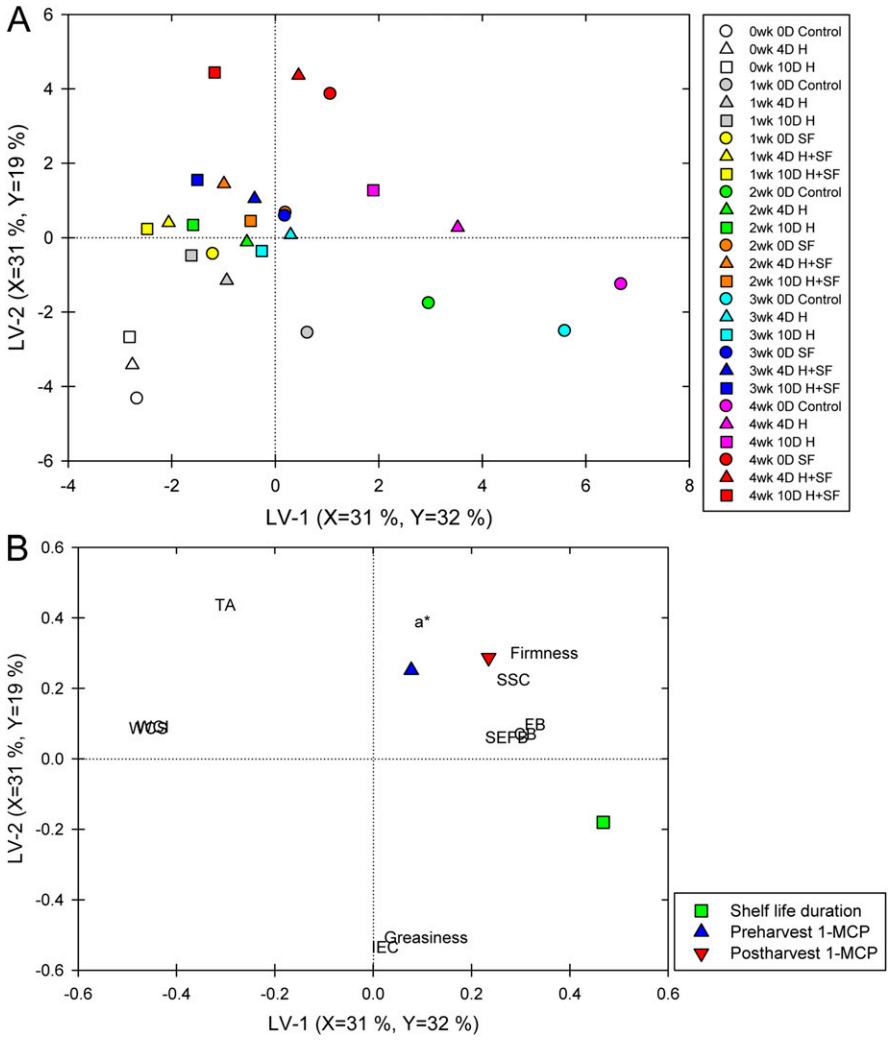


Fig. 2. Partial least squares regression scores (A) and loading (B) plots of models containing X-variables (fruit quality attributes and incidence of physiological disorders) and Y-variables [experimental factors: storage duration, ■; preharvest 1-MCP (Harvista) treatment, ▲; postharvest 1-MCP (SmartFresh) treatment, ▼] for preharvest (Harvista, or H) and postharvest (SmartFresh, or SF) 1-MCP treatments in combination or alone in 'Fuji' apples at 20 °C. CB, core browning; FB, flesh browning; IEC, internal ethylene concentration; SEFB, stem-end flesh browning; SSC, soluble solids concentration; TA, titratable acidity; WCI, watercore incidence; WCS, watercore severity.

The PLS loading plot (Fig. 2B) shows that postharvest 1-MCP treatment was strongly associated with firmness and SSC, whereas preharvest 1-MCP treatment was linked with the *a** value. Storage time, however, was less strongly associated with other fruit quality variables, indicating that postharvest 1-MCP treatment more effectively maintained fruit quality attributes, such as firmness and SSC, than preharvest 1-MCP treatment during storage. Furthermore, fruit peel with a red to yellow color, as reflected by *a** values, was influenced by preharvest 1-MCP treatment during storage.

*Storage at 0.5 °C.* Both IEC and flesh firmness were affected by a three-way interaction of storage duration, preharvest 1-MCP treatment, and postharvest 1-MCP treatment (Table 4). Ethylene production during storage as indicated by IEC was delayed by preharvest 1-MCP treatment and to a greater extent with treatment at 10 DBH than at 4 DBH. In contrast, the IEC of fruit treated with postharvest 1-MCP remained low and decreased over time, but without the effects of preharvest 1-MCP. Firmness of the untreated fruit declined during storage, but it was not significantly different from that of the preharvest 1-MCP–treated fruit until week 12. The timing of preharvest 1-MCP had no significant effect on firmness. No effects of preharvest 1-MCP treatment on the responses of fruit to postharvest 1-MCP were detected.

TA declined during cold storage, and preharvest 1-MCP treatments slowed, but did not prevent, its loss over time (Table 4). The timing of preharvest 1-MCP treatment had no consistent effects. Postharvest 1-MCP treatment resulted in greater maintenance of TA in fruit without preharvest 1-MCP treatment and in fruit with all preharvest treatments in general. SSCs were affected only by storage time and postharvest 1-MCP treatment. The *a** values were greatly affected by either storage time or postharvest 1-MCP treatment, and by the interaction of storage time and postharvest 1-MCP treatment.

Greasiness was affected by three main factors (storage time, preharvest 1-MCP treatment, and postharvest 1-MCP treatment) and the two-way interactions between storage time and preharvest 1-MCP treatment or postharvest 1-MCP treatment (Table 5). Effects of postharvest 1-MCP were significant but not consistent, with considerable variability across storage time. Greasiness actually had declined at the last sampling time (36 weeks). The incidence and severity of watercore decreased over time in storage, regardless of postharvest 1-MCP treatment (Table 5). The effects of preharvest 1-MCP treatment were affected by storage time. Stem-end flesh browning was only detected in fruit without either preharvest or postharvest 1-MCP treatment. Decay increased in fruit as storage time increased.

Preharvest and postharvest 1-MCP treatments were positively or negatively correlated with fruit quality depending on the attributes during storage at 0.5 °C (Fig. 3). IEC was negatively correlated with firmness, TA, SSC, *a**, and watercore incidence, but it was positively correlated with greasiness and stem-end flesh browning. Firmness was positively correlated with TA, SSC, and *a**, but it was negatively correlated with greasiness and stem-end flesh browning. TA was positively correlated with watercore incidence and watercore severity, but it was negatively correlated with greasiness, stem-end flesh browning, fruit rot, and fruit shrivel. SSC was positively correlated with *a**. The *a** values were negatively correlated with stem-end flesh browning. Greasiness was positively correlated with fruit rot, but it was negatively correlated with the incidence and severity of watercore. The correlation responses of watercore incidence were mostly similar to those of watercore severity. Decay was positively correlated with shrivel.

The PLS scores plot (Fig. 4A) illustrates that the results of preharvest and postharvest 1-MCP treatments were closely associated with each other as storage time increased; however, untreated fruit were outliers compared with the results of fruit with preharvest and postharvest 1-MCP treatment, in combination or alone, after 12 weeks of cold storage. The results of fruit treated only with preharvest 1-MCP, either 4 or 10 DBH, were closely associated with the responses of fruit treated with both preharvest and postharvest 1-MCP.

The PLS loading plot (Fig. 4B) describes a close association between preharvest and postharvest 1-MCP treatments for SSC and *a** values, but that storage time was associated with greasiness and decay. In contrast,

Table 4. Internal ethylene concentration (IEC), flesh firmness, titratable acidity (TA), soluble solids concentration (SSC), and *a** values of 'Fuji' apples stored at 0.5 °C for up to 36 weeks followed by 1 d at 20 °C.[z]

| Storage time (wk) | Harvista treatment (DBH)[a] | Log IEC[b] (μL L$^{-1}$) | | Firmness (N) | | TA (%) | | SSC (%) | | *a** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | – | + | – | + | – | + | – | + | – | + |
| 0 | – | 0.2 | | 66.2 | | 0.350 | | 12.7 | | 28.9 | |
| | 4 | 0.2 | | 67.8 | | 0.333 | | 12.7 | | 29.9 | |
| | 10 | 0.1 | | 66.6 | | 0.326 | | 12.4 | | 30.0 | |
| 6 | – | 1.7 | 0.0 | 68.8 | 69.1 | 0.263 | 0.280 | 12.4 | 12.9 | 28.7 | 28.7 |
| | 4 | 0.7 | –0.1 | 68.2 | 69.2 | 0.276 | 0.291 | 13.0 | 13.2 | 30.6 | 29.8 |
| | 10 | 0.4 | 0.0 | 68.2 | 70.6 | 0.278 | 0.305 | 12.8 | 13.0 | 30.1 | 28.6 |
| 12 | – | 2.1 | 0.1 | 65.1 | 68.3 | 0.206 | 0.263 | 12.7 | 13.1 | 30.3 | 30.6 |
| | 4 | 1.3 | 0.1 | 68.9 | 67.3 | 0.236 | 0.258 | 12.3 | 12.4 | 31.2 | 31.0 |
| | 10 | 0.8 | 0.1 | 69.3 | 68.9 | 0.236 | 0.239 | 12.1 | 12.5 | 28.8 | 30.8 |
| 18 | – | 2.1 | –0.2 | 64.3 | 69.0 | 0.154 | 0.248 | 13.0 | 13.0 | 31.1 | 30.7 |
| | 4 | 1.4 | –0.2 | 68.7 | 69.0 | 0.204 | 0.214 | 13.0 | 13.0 | 30.7 | 31.0 |
| | 10 | 1.0 | –0.1 | 68.7 | 68.9 | 0.204 | 0.221 | 12.8 | 13.0 | 30.5 | 31.5 |
| 24 | – | 2.3 | –0.2 | 56.8 | 72.2 | 0.115 | 0.208 | 12.2 | 12.2 | 29.6 | 30.9 |
| | 4 | 1.4 | –0.3 | 67.9 | 72.8 | 0.197 | 0.197 | 12.4 | 12.5 | 30.8 | 30.9 |
| | 10 | 1.3 | –0.2 | 68.8 | 71.3 | 0.187 | 0.201 | 13.1 | 12.0 | 31.3 | 29.7 |
| 30 | – | 2.3 | –0.5 | 54.4 | 72.6 | 0.065 | 0.151 | 12.2 | 13.0 | 29.4 | — |
| | 4 | 1.3 | –0.5 | 69.8 | 69.7 | 0.122 | 0.137 | 12.8 | 13.2 | 31.2 | — |
| | 10 | 1.4 | –0.4 | 68.4 | 71.4 | 0.132 | 0.151 | 12.7 | 12.6 | 30.1 | — |
| 36 | – | 2.4 | –0.5 | 54.4 | 69.0 | 0.057 | 0.110 | 12.4 | 13.3 | 28.0 | 30.0 |
| | 4 | 1.7 | –0.4 | 69.8 | 68.5 | 0.085 | 0.102 | 12.9 | 13.0 | 29.8 | 30.7 |
| | 10 | 1.2 | –0.4 | 68.4 | 68.4 | 0.097 | 0.115 | 12.8 | 12.9 | 29.5 | 29.6 |
| | $LSD_{0.05}$ | 0.33 | | 2.5 | | 0.0189 | | 0.77 | | 2.44 | |
| Significance | | | | | | | | | | | |
| Storage time (T) | | **<0.0001** | | **0.0001** | | **<0.0001** | | **0.0054** | | **<0.0001** | |
| Harvista (H) | | **<0.0001** | | **<0.0001** | | **0.0070** | | 0.4375 | | 0.0755 | |
| SmartFresh (S) | | **<0.0001** | | **<0.0001** | | **<0.0001** | | **0.0228** | | **<0.0001** | |
| T×H | | **<0.0001** | | **<0.0001** | | **0.0150** | | 0.3152 | | 0.9853 | |
| T×S | | **<0.0001** | | **<0.0001** | | 0.6293 | | 0.1638 | | **<0.0001** | |
| H×S | | **<0.0001** | | **<0.0001** | | **<0.0001** | | 0.1146 | | 0.5541 | |
| T×H×S | | **<0.0001** | | **<0.0001** | | 0.1328 | | 0.6294 | | 0.7454 | |

[z]Fruit were untreated or treated with preharvest 1-MCP (Harvista) at 4 or 10 d before harvest (DBH) and untreated (–) or treated (+) with postharvest 1-MCP.

Table 5. Greasiness incidence, watercore incidence and severity, and incidences of stem-end browning, decay and shrivel of 'Fuji' apples stored at 0.5 °C for up to 36 weeks followed by 1 d at 20 °C.[z]

| Storage time (wk) | Harvista treatment (DBH) | Greasiness (%) | | Watercore incidence (%) | | Watercore severity (0–3) | | Stem-end browning (%) | | Decay (%) | | Shrivel (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | – | + | – | + | – | + | – | + | – | + | – | + |
| 0 | – | 0 | | 85 | | 1.4 | | 0 | | 0 | | 0 | |
| | 4 | 0 | | 80 | | 1.5 | | 0 | | 0 | | 0 | |
| | 10 | 0 | | 55 | | 0.7 | | 0 | | 0 | | 0 | |
| 6 | – | 30 | 40 | 33 | 23 | 1.6 | 1.7 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4 | 28 | 38 | 23 | 18 | 0.7 | 0.7 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 10 | 23 | 23 | 13 | 15 | 0.9 | 0.8 | 0 | 0 | 3 | 0 | 0 | 0 |
| 12 | – | 63 | 28 | 5 | 3 | 0.4 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4 | 23 | 23 | 3 | 3 | 0.3 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 10 | 13 | 10 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 18 | – | 88 | 60 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 5 | 5 | 0 | 0 |
| | 4 | 70 | 48 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 3 | 5 | 0 | 0 |
| | 10 | 55 | 38 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 5 | 8 | 0 | 3 |
| 24 | – | 68 | 35 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 5 | 8 | 0 | 3 |
| | 4 | 65 | 50 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 3 | 0 | 0 | 0 |
| | 10 | 55 | 35 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 3 | 8 | 0 | 3 |
| 30 | – | 93 | 68 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 8 | 5 | 25 | 13 |
| | 4 | 93 | 93 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 3 | 0 | 28 | 35 |
| | 10 | 98 | 68 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 5 | 3 | 43 | 20 |
| 36 | – | 13 | 28 | 0 | 0 | 0.0 | 0.0 | 12 | 0 | 1 | 8 | 20 | 29 |
| | 4 | 28 | 35 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 7 | 13 | 47 | 31 |
| | 10 | 23 | 33 | 0 | 0 | 0.0 | 0.0 | 0 | 0 | 4 | 11 | 52 | 68 |
| | $LSD_{0.05}$ | 17.5 | | 11.4 | | 0.6 | | 1.4 | | 7.4 | | 13.5 | |
| Significance | | | | | | | | | | | | | |
| Storage time (T) | | **<0.0001** | | **<0.0001** | | **<0.0001** | | **<0.0001** | | **<0.0001** | | **<0.0001** | |
| Harvista (H) | | **0.0001** | | **0.0028** | | **0.0220** | | **0.0002** | | 0.4490 | | **0.0026** | |
| SmartFresh (S) | | **<0.0001** | | 0.5521 | | 0.8889 | | **0.0003** | | 0.1801 | | 0.5089 | |
| T×H | | **0.0002** | | **0.0054** | | **0.0050** | | **<0.0001** | | 0.2863 | | **<0.0001** | |
| T×S | | **<0.0001** | | 0.9378 | | 1.0000 | | **<0.0001** | | 0.1332 | | 0.2874 | |
| H×S | | 0.0641 | | 0.7663 | | 0.9169 | | **<0.0001** | | 0.8313 | | 0.9829 | |
| T×H×S | | 0.2241 | | 0.9963 | | 0.9998 | | **<0.0001** | | 0.9476 | | **0.0381** | |

[z]Fruit were untreated or treated with preharvest 1-MCP (Harvista) at 4 or 10 d before harvest (DBH) and untreated (–) or treated (+) with postharvest 1-MCP.

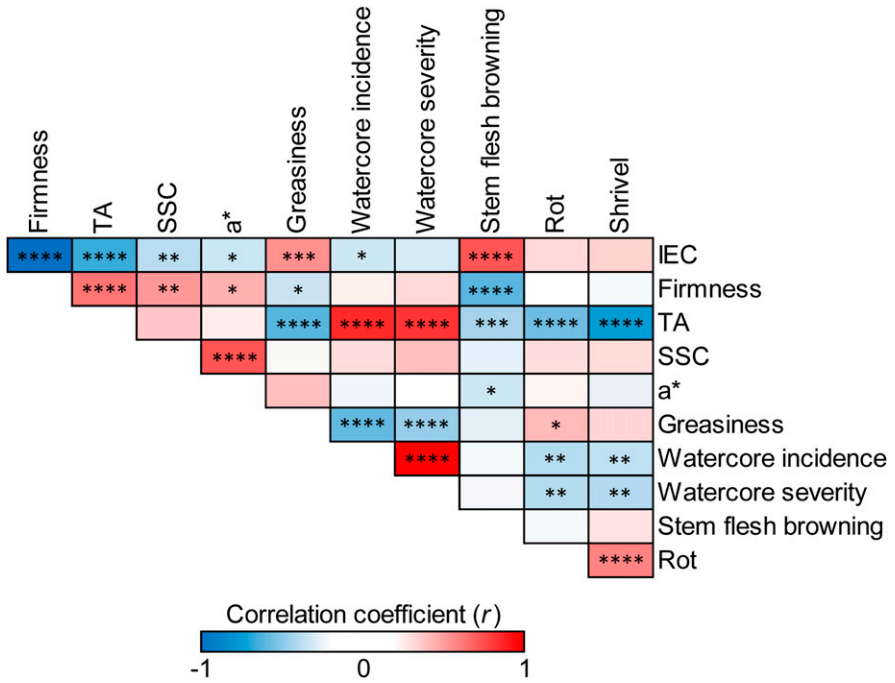


Fig. 3. Pearson correlation coefficient ($r$) matrix for fruit quality attributes and the incidence of physiological disorders with preharvest (Harvista) and postharvest (SmartFresh) 1-MCP treatments in combination or alone in 'Fuji' apples stored in air for up to 36 weeks at 0.5 °C followed by 1 d at 20 °C. IEC, internal ethylene concentration; TA, titratable acidity; SSC, soluble solids concentration. Red and blue colors represent positive and negative correlations between factors. *, **, ***, or **** indicate statistically significant correlations at $P < 0.05$, 0.01, 0.001, or 0.0001, respectively.

TA and the incidence and severity of watercore were less associated with the storage time variable. Firmness was closely associated with preharvest or postharvest 1-MCP treatment. IEC was closely linked with stem-end flesh browning.

## Discussion

The effects of preharvest 1-MCP, alone and in combination with postharvest 1-MCP, on fruit quality attributes of 'Fuji' stored for up to 4 weeks at 20 °C and 36 weeks at 0.5 °C have been investigated. Preharvest 1-MCP treatment delayed maturity, as indicated by lower SPI values and by reduced watercore, although other harvest indices were not influenced by treatment. Yuan and Li (2008) and Yuan and Carbaugh (2007) reported that preharvest 1-MCP treatment delayed starch hydrolysis in 'Bisbee Delicious' and 'Golden Delicious' apples at harvest, which was in contrast to the results of Elfving et al. (2007), who used 'Delicious'.

Starch hydrolysis was highly affected by ethylene production in 'Gala' apples (Doerflinger et al., 2015a). Doerflinger et al. (2015b) reported that IEC was positively correlated with SPI over a wide range of fruit maturities for 'Gala', 'Honeycrisp', 'McIntosh', and 'Empire' apples. These relationships were consistent with the results of our study, which indicated that starch hydrolysis progression and increased IEC were highly correlated. Starch degradation may be ethylene-independent or ethylene-dependent, and it varies with the cultivar (Thammawong and Arakawa, 2007). Johnston et al. (2009) found that starch degradation in harvested fruit was sensitive to low ethylene concentrations, but that it had low dependence on increasing ethylene concentrations.

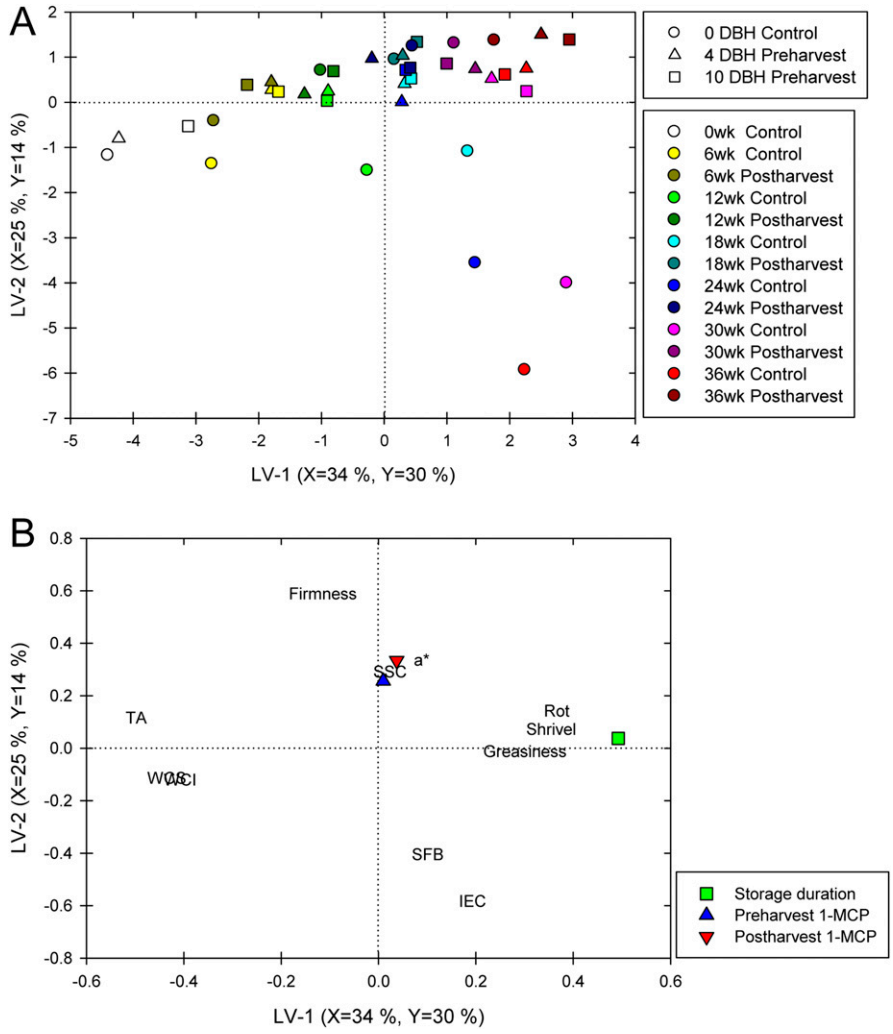


Fig. 4. Partial least squares regression scores (**A**) and loading (**B**) plots of models containing X-variables (fruit quality attributes and incidence of physiological disorders) and Y-variables [experimental factors: cold storage duration, ■; preharvest 1-MCP (Harvista) treatment, ▲; postharvest 1-MCP (SmartFresh) treatment, ▼] for preharvest (Harvista, or H) and postharvest (SmartFresh, or SF) 1-MCP treatments in combination or alone in 'Fuji' apples stored in air for up to 36 weeks at 0.5 °C followed by 1 d at 20 °C. IEC, internal ethylene concentration; SFB, stem-end flesh browning; SSC, soluble solids concentration; TA, titratable acidity; WCI, watercore incidence; WCS, watercore severity.

IEC, firmness, and TA were affected by the preharvest and postharvest 1-MCP treatments during storage at 20 and 0.5 °C, but SSC was only affected by the postharvest 1-MCP treatment (Tables 2 and 4). Preharvest and postharvest treatments delayed softening in air and CA storage of 'McIntosh' and 'Delicious' apples, but the postharvest 1-MCP treatment was more effective maintaining firmness than the preharvest 1-MCP treatment alone (Watkins et al., 2010). The shorter the time between preharvest 1-MCP treatment and harvest, the firmer the fruit and the lower the IEC for 'Delicious' apple, although there was no direct effect of the ethylene concentration on firmness during the storage of fruit treated with preharvest and postharvest 1-MCP (Elfving et al., 2007; Lee et al., 2016). Postharvest 1-MCP treatment maintained higher TA than no treatment during cold storage as the IEC was suppressed, but it did not affect the responses of SSC (DeEll and Ehsani-Moghaddam, 2013). Loss of acidity is similar to starch degradation, with low dependency on, but high sensitivity to, ethylene (Johnston et al., 2009). In contrast, color change and flesh softening have high dependency on and low sensitivity to ethylene.

SSC was only affected by postharvest 1-MCP treatment during storage at 20 and 0.5 °C (Tables 2 and 4). Preharvest 1-MCP treatments also did not affect the SSC of 'Golden Delicious' apple at harvest (Yuan and Carbaugh, 2007), but they reduced the SSC at harvest of 'Delicious' apple (Elfving et al., 2007). Interestingly, SSC was closely associated with the postharvest 1-MCP treatment alone at 20 °C (Fig. 2B) and with both preharvest and postharvest 1-MCP treatments at 0.5 °C (Fig. 4B). This result could be associated with the low storage temperature, which would further reduce fruit respiration compared with ambient temperatures. Therefore, fruit quality management during shelf life and cold storage would be further enhanced by the combination of preharvest and postharvest 1-MCP applications rather than by preharvest 1-MCP application alone. In addition, the Pearson correlation analysis indicated that SSC was negatively correlated with IEC, but that IEC was positively correlated with peel greasiness. Peel greasiness was also negatively correlated with the fruit firmness of 'Empire' and 'Ambrosia' apples during storage (Ehsani-Moghaddam and DeEll, 2009).

The responses of fruit peel color as indicated by the *a** values were unaffected by preharvest 1-MCP application at harvest, but they were affected by storage time and postharvest 1-MCP treatment during long-term cold storage (Tables 1, 2, and 4). This indicates that the loss of green color is more responsive to postharvest 1-MCP treatment than preharvest 1-MCP treatment during storage at either 0.5 or 20 °C. The *a** values were negatively correlated with IEC but positively correlated with SSC, irrespective of the storage temperature (Figs. 1 and 3). Furthermore, Ehsani-Moghaddam and DeEll (2009) reported that among fruit ripening attributes, IEC and SSC were negatively correlated in 'Empire' and 'Ambrosia' apples during storage. However, *a** and SSC were more closely associated during storage at 0.5 °C than at 20 °C (Figs. 2 and 4), indicating that the preharvest plus postharvest 1-MCP applications were better able to maintain peel color in cold storage than in warm storage. Low temperature is a well-known critical factor for maintaining greenness and SSC during storage.

Fruit greasiness is associated with alterations in the quantity and chemical composition of fruit surface lipids in the epidermal cells during fruit ripening (Veraverbeke et al., 2001; Yang et al., 2017a, 2017b). Peel greasiness was positively correlated with IEC in 'Empire' and 'Ambrosia' apples during storage (Ehsani-Moghaddam and DeEll, 2009), and postharvest 1-MCP treatments can reduce greasiness development during storage for 'Empire' apple (Nock and Watkins, 2013). In our study, the incidence of greasiness was higher for control fruit than for fruit treated with preharvest plus postharvest 1-MCP treatments at 20 °C (Table 2), but the incidence was relatively less consistent with 1-MCP treatment at 0.5 °C (Table 4). Greasiness was correlated with IEC at 20 °C to a greater extent than it was at 0.5 °C (Figs. 1 and 3), suggesting that the association of greasiness and IEC was much greater at warmer than at cooler temperatures (Figs. 2B and 4B). This result indicated that the preharvest plus postharvest 1-MCP treatments more effectively controlled fruit ripening at 20 °C, thereby delaying the development of greasiness.

Watercore incidence was also reduced by preharvest 1-MCP treatment in 'Bisbee Delicious' apple (Yuan and Li, 2008), but not in 'Scarletspur Delicious' apple (Elfving et al., 2007). The effects of preharvest 1-MCP

treatment on starch hydrolysis and watercore incidence could be dependent on the apple cultivar or variety. Watercore can develop in the fruit before harvest due to differences in diurnal temperature (Sugiura et al., 2013). 'Fuji' fruit are highly susceptible to watercore development. Preharvest 1-MCP slightly reduced the incidence of watercore at harvest, and the symptoms of watercore dissipated earlier in the preharvest 1-MCP–treated fruit than the control fruit during storage at either temperature (Tables 1, 3, and 5). However, postharvest 1-MCP treatment alone was not consistently effective at either 0.5 or 20 °C compared with preharvest 1-MCP treatment alone. Interestingly, although watercore incidence was associated with higher sorbitol and sucrose contents (Bowen and Watkins, 1997), the incidence and severity of watercore were neither correlated with SSC (Figs. 1 and 3) nor closely associated with SSC at 20 °C or during storage at 0.5 °C (Figs. 2B and 4B).

The presence of watercore at harvest can be associated with the development of physiological disorders, such as flesh browning, stem-end flesh browning, core browning, core flush, and $CO_2$ injury during long-term storage (Argenta et al., 2000). In this study, browning incidences were negatively correlated with the incidence and severity of watercore during storage at 0.5 and 20 °C, as indicated by PLS loading plots (Fig. 2B) and cold storage (Fig. 4B). However, preharvest and postharvest 1-MCP treatments did not consistently affect the incidence of physiological disorders at 20 °C (Table 3) or at 0.5 °C (Table 5). Interestingly, fruit shrivel increased with storage time and was further aggravated by the preharvest 1-MCP treatment during cold storage. It is possible that preharvest 1-MCP treatment could contribute to greater susceptibility of fruit to water loss during cold storage if it is associated with less wax accumulation. Postharvest 1-MCP treatment delayed the development of certain wax constituents in cold-stored 'Royal Gala' apple (Curry, 2008). During storage at both 20 and 0.5 °C, preharvest 1-MCP treatment reduced the incidence rate of greasiness. However, Dong et al. (2012) reported that the total wax level was reduced during cold storage, but that postharvest 1-MCP treatment delayed the reduction of the total wax level in cold-stored 'Red Fuji' apple. Postharvest 1-MCP treatment had no effect on the incidence of shrivel, even though it might be affected by wax contents and constituents.

In conclusion, in addition to the effects of preharvest or postharvest 1-MCP treatment alone on the management of fruit quality attributes and physiological disorders, combined preharvest and postharvest 1-MCP treatments might have a wide range of advantages for fruit growers and storage operators. The effects of preharvest 1-MCP were more consistent when the interval between spraying and harvest was 10 DBH compared with 4 DBH. Preharvest plus postharvest 1-MCP applications contributed to the maintenance of fruit quality attributes and control of physiological disorders during storage at both 0.5 and 20 °C. Plots of the PLS scores indicated that preharvest plus postharvest 1-MCP applications were much more effective for fruit quality management during storage at 20 °C than at 0.5 °C. It is also possible that cold storage is effective for maintaining fruit quality and, therefore, masked the effects of 1-MCP. Overall, preharvest plus postharvest 1-MCP applications might be beneficial for maintaining apple fruit quality, not only during long-term cold storage but also in less optimal storage temperatures.

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