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Fruit maturity, controlled atmosphere delays and storage temperature affect fruit quality and incidence of storage disorders of 'Fuji' apples

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ABSTRACT

The effects of storage temperature, harvest maturity, controlled atmosphere (CA) storage regime, and CA strategies on fruit quality and the incidence of storage disorders during storage of 'Fuji' apples [*Malus sylvestris* (L.) Mill var. *domestica* (Borkh.) Mansf.] were investigated. Flesh browning incidence was lower in fruit stored at 2 °C than at 0 °C, but fruit were also softer and had lower titratable acidity (TA) at the higher storage temperature. All subsequent studies were carried out at 0 °C. High partial pressures of CO_2 (pCO_2) of 2.5 kPa compared with <1 kPa did not consistently affect flesh firmness, soluble solids concentration (SSC), and TA. The incidence of flesh browning was higher in more mature fruit and it was further aggravated by higher pCO_2 in the storage atmosphere, irrespective of pO_2, while watercore disappearance was more rapid at <1 kPa CO_2 than at 2.5 kPa CO_2. Flesh browning was also higher at 1.5 kPa CO_2 than at <1 kPa CO_2, although ethylene production was lowest at 1.5 kPa pCO_2. Stepwise delay of high CO_2 or low O_2 CA storage did not affect flesh firmness, TA, internal ethylene concentration, respiration rate, and ethylene production, but watercore disappearance was more rapid, compared with standard CA storage at 2 months. Flesh browning was not detected in the stepwise CO_2 delayed CA treatment and low CO_2 CA storage (<0.2 kPa CO_2), but a low (<4%) incidence of flesh browning was found in a delayed CA treatment and standard CA storage. These results indicate that 'Fuji' apples could be stored at 0 °C in 1–2 kPa O_2/<1 kPa CO_2 if harvested at less than 190 days after full bloom. Stepwise CO_2 delay CA or low CO_2 CA storage regimes are recommended to retard the loss of fruit quality factors and reduce development of CA-related storage disorders.

1. Introduction

The 'Fuji' apple has been extensively planted and has become the most popular commercial apple cultivar in Korea due to its distinctive juiciness, crispness, sweetness, and attractive appearance. However, the cultivar is typically harvested at advanced maturity to meet the required quality characteristics, such as maximum red coloration and high soluble solids concentration (SSC) (Park et al., 1997), but fruit harvested at this stage may enhance incidence and severity of watercore (Argenta et al., 2002b; Bowen and Watkins, 1997; Harker et al., 1999). The appearance and development of watercore is associated with a sharp increase in sorbitol concentrations (Williams and Billingsley, 1973) and flooding of fruit tissues near the fruit core or vascular bundles with sorbitol-rich translocate (Marlow and Loescher, 1984). Although sorbitol accumulation in tissues of apple fruit was associated with higher SSC, watercore development is not desirable in the marketplace (Bowen and Watkins, 1997; Choi, 1997; Watkins et al., 1993). 'Fuji' apples appear tolerant of watercore-associated breakdown compared with other apple cultivars (Bowen and Watkins, 1997). However, the cultivar is susceptible to flesh browning, sometimes associated with severe watercore at harvest, core browning (syn. core flush), core breakdown, brown heart, and CO_2 injury, especially during CA storage (Argenta et al., 2000, 2002a,b; Choi, 1997; Park et al., 1997; Park and Lee, 1992).

Research has focused on management strategies to improve the maintenance of fruit quality and reduce or inhibit the incidence of

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physiological storage disorders in 'Fuji'. Rapid CA resulted in higher incidences of brown heart, core browning, and flesh breakdown, which were lower in <1 kPa CO_2 and depending on fruit maturity, reduced by delays before CA storage (Argenta et al., 2000; Kweon et al., 1998). A stepwise increase in pCO_2 after maintaining ≤1 kPa CO_2 early in the storage period also reduced CO_2 injury and flesh browning (Argenta et al., 2000; Chung et al., 2005). Delayed increases of pCO_2 allow reduction of injury while not compromising quality factors, such as flesh firmness and titratable acidity (Argenta et al., 2000; Chung et al., 2005). No studies on storage temperature and its relationship to partial pressures of O_2 and CO_2 are available for 'Fuji'. In other cultivars, storage temperatures also influence the incidence of storage disorders, such as internal browning, low temperature breakdown, core browning, and vascular breakdown during CA storage (Chu, 1999; DeEll and Prange, 1998; Watkins and Liu, 2010). Research on the interactions of these gases with harvest maturity is also limited.

The objective of this study was to evaluate the effects of storage temperature, harvest maturity, and CA strategies on fruit quality parameters, such as flesh firmness, SSC, TA, IEC, ethylene production and respiration rate, and the incidence and severity of physiological storage disorders including watercore and flesh browning in CA stored 'Fuji' apple fruits.

2. Materials and methods

2.1. Plant material

'Fuji' apple [*Malus sylvestris* (L.) Mill var. *domestica* (Borkh.) Mansf.] fruit used in these experiments were harvested from mature trees grown at the experimental orchard of Apple Research Station, National Institute of Horticultural & Herbal Science, RDA, in Kunwi, Gyeongbuk, Republic of Korea, unless indicated otherwise. For each experiment described below, fruit quality at harvest was assessed by slicing three replicates of 30 fruit for evaluation of watercore severity and starch pattern indices.

2.2. Storage temperature and CA storage regimes

To investigate the effects of storage temperatures on fruit quality parameters and flesh browning incidence during CA storage, 310 fruit were randomly harvested at 185 days after full bloom (DAFB). After the 90 fruit were used for harvest assessments, 110 fruit were cooled overnight either at 0 or 2 °C and placed into CA chambers with dimensions of 1.3 m × 1.5 m × 1.8 m. At each storage temperature, a final CA atmosphere regime of 2.5 kPa O_2/2.5 kPa CO_2 was established within 3 days, and fruit then stored for 6 months. The atmosphere in each chamber was controlled by adding nitrogen gas from N_2 generator (NPO-0.75, Fuji Plant, Japan). The CAs were adjusted and monitored by a gas sampling system (O_2 Controller and CO_2 Controller, Fuji Plant, Japan). During CA storage, the pO_2 and pCO_2 was maintained at the set points ±0.5 kPa. Where necessary, CO_2 was added, and calcium oxide was used to scrub excessive CO_2. After 6 months of CA storage plus 1 day at 20 °C, flesh firmness, SSC, and TA were assessed on 3 lots of 10 fruit, while storage disorders were assessed on 4 lots of 20 fruit. Each fruit was cut at least three times equatorially to determine the incidence of flesh browning.

2.3. Effect of harvest time and pO_2 and pCO_2

At 170 and 200 DAFB, 530 fruit were harvested, 90 fruit used for evaluation of fruit maturity, and remaining fruit divided into 4 groups for storage at 0 °C. CA regimes of 1.5 or 2.5 kPa O_2 with <1 or 2.5 kPa CO_2, in chambers (0.8 m × 0.8 m × 1.0 m) were established within 3 days and fruit stored for 6 months. After 1 day at 20 °C, flesh firmness, SSC, and TA were assessed on 3 lots of 10 fruit, while storage disorders were assessed on 4 lots of 20 fruit. Each fruit was cut at least three times equatorially to determine the incidence of flesh browning.

Two additional experiments were carried out. In the first, 400 fruit per treatment were harvested at 200 DAFB and then stored at 0 °C in CA chambers (0.8 m × 0.8 m × 1.0 m). CA regimes of 1.5 or 2.5 kPa O_2 with <1 or 2.5 kPa CO_2 were established within 3 days and fruit stored for 6 months. Watercore was assessed every month after 2 months of CA storage using 4 replicates of 20 fruit.

In the second experiment, 530 fruit were harvested at 190 DAFB 90 fruit used for harvest maturity evaluation. The remaining fruit were stored at 0 °C for 6 months at <1 kPa or 1.5 kPa CO_2 in either 1.5 or 2.5 kPa O_2. After removal from storage 3 lots of 10 fruit were used for fruit quality, respiration rate, and ethylene production rate, and 4 lots of 20 fruit used to evaluate flesh browning after 1 day at 20 °C.

2.4. CA strategies

To assess stepwise CA strategies, 530 fruit (90 fruit for harvest quality assessment and 440 fruit for stored fruit assessment) were harvested at 190 DAFB from a commercial apple orchard in Andong, Korea and stored at 0 °C for 20 days. Final CA regimes with 110 fruit per treatment were established as follows:

(1) Standard CA storage: fruits were stored at 0 °C for 20 days and 2.5 kPa O_2/1.5 kPa CO_2 established within 1 day.
(2) Stepwise CO_2 CA: fruits were stored at 0 °C for 20 days, 2.5 kPa O_2/0.2 kPa CO_2 established and maintained for 1 month. The pCO_2 was then increased to 1.5 kPa.
(3) Stepwise O_2 CA: fruits were stored at 0 °C air for 20 days, the pCO_2 increased to 1.5 kPa for 1 month. The pO_2 was reduced to 2.5 kPa for the last 10 days.
(4) Low CO_2 CA: fruits were stored at 0 °C for 20 days, and 1.5 kPa O_2/0.25 kPa CO_2 then established.

After fruit were removed from storage after total 2 months from harvest, SSC, TA, and firmness as well as physiological storage disorders, were assessed.

2.5. Fruit assessments

At harvest, Hunter a value was measured with chromameter (CR-400, Konica Minolta Sensing, Inc., Japan) on the equatorial region of fruit peel with three readings per fruit. The starch pattern index at harvest, and water core at harvest and after storage, were evaluated by horizontally slicing on the equatorial region. The watercore severity was obtained by assessing the % of tissue with watercore: 0 = 0%; 1 = 1–10%, 2 = 11–20%, 3 = 21–30%, 4 = 31–40%, and 5 = 41–100% (Kweon et al., 1998). The same sliceswere used for evaluating starch pattern index by spraying iodine solution on the slices and rating the % staining, where 0 = 0%, 1 = 1–14%, 2 = 15–39%, 3 = 40–59%, 4 = 60–79%, and 5 = 80–100%.

Internal ethylene concentrations (IECs) were determined by withdrawing a 1 mL gas sample from the core cavity of each apple fruit. The sample was injected into a Hewlett-Packard 6890 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 run isothermally with an oven temperature of 70 °C and injector and detector temperature of 100 and 200 °C, respectively. The flow rate of He was 20 mL min^{-1}. Ethylene was quantified by peak area using an external standard used for calibration.

To measure ethylene production and respiration rates, 10 fruit were placed into sealed 1.6 L plastic containers fitted with