Harvest maturity highly affects fruit quality attributes of ethylene-treated ‘autumn sense’ hardy kiwifruit

Hyowon Park, Mahn-Jo Kim, Chul-Woo Kim, Narae Han and Uk Lee

Division of Special Forest Resources, National Institute of Forest Science, Dongdaemun-gu, Republic of Korea

ABSTRACT
Optimal harvest date is an important quality parameter for hardy kiwifruit. We, therefore, examined the ideal harvest date to obtain high-quality ripe “Autumn sense” hardy kiwifruit. The fruit was harvested at four different harvest maturity stages (6.2%, 7.1%, 8.1%, and 9.1% average soluble solids content (SSC); H1, H2, H3, and H4, respectively), then treated with exogenous ethylene at ambient temperature, to examine the quality of the ripening fruit. The four harvest maturity stages differed significantly in firmness, SSC, titratable acidity (TA), and SSC/TA ratio, both in freshly harvested and ripe hardy kiwifruit (p < 0.001). Fruit firmness at harvest gradually decreased from 32.1 to 25.1 N, while SSC increased steadily as harvest maturity increased. TA increased steadily from 0.8 in H1 to 1.1% in H3, and was lower in H4. After ethylene treatment, the range of firmness was much lower, at 2.7–3.1 N, while SSC increased significantly from 15.1% in H1 to 16.4% in H4. TA decreased significantly from 1.0% at harvest to 0.7% after ethylene treatment, regardless of harvest maturity stage. For H3 fruit, TA was 56% lower after ethylene treatment than before treatment. After treatment, H3 had the highest SSC/TA (p < 0.001). Consumer preference was higher for H3 and H4 than H1 and H2, and was highly correlated with the SSC/TA ratio at harvest and after ethylene treatment, and with SSC at harvest. These results suggest that TA, SSC, and SSC/TA should be considered for determining the optimal harvest maturity for hardy kiwifruit. This study reveals that the quality of ripened hardy kiwifruit can be maximized by controlling harvest maturity.

Introduction
Hardy kiwifruit Actinidia arguta (Siebold & Zucc.) Planch. ex Miq. is known as “kiwiberry” or “baby kiwifruit,” has a unique intense aromatic flavor and a well-balanced sour/sweet taste (Fisk et al. 2006). In South Korea, interest in A. arguta cultivation and consumption is steadily increasing, because of its geographic and climatic advantages which have resistance to winter cold weather, enduring temperature at −38°C (Cossio et al. 2015; Ahn et al. 2020). It contains more bioactive compounds and nutrients such as polyphenols, flavonoids, tannins, and vitamin C, than other kiwifruit varieties, the fuzzy kiwifruit A. delicosa and A. eriantha (Krupa et al. 2011; Leontowicz et al. 2016). It contains high levels of lutein and of minerals, especially P, Ca, Fe, and Zn (Nishiyama et al. 2005; Fisk et al. 2008).

As hardy kiwifruit has high autocatalytic ethylene production and respiration rates after harvest, it is regarded as a typical climacteric fruit (Pech et al. 2008; Lim et al. 2016). As vine-ripe fruit is highly vulnerable to reductions in fruit quality during distribution and in the market because of their tendency to soften, they are commonly harvested when they are physiologically mature but still firm (Fisk et al. 2006). Developing a harvest maturity index is therefore very important for improving postharvest quality parameters such as sensory quality, nutritional value, marketability, and storability, in order to effectively commercialize hardy kiwifruit (Oh et al. 2017). For hardy kiwifruit, however, the criteria for determining the optimal harvest maturity to achieve the required ripening characteristics remain unclear.

According to Fisk et al. (2006), A. arguta “Ananasnaya” has commonly been harvested at a soluble solids content (SSC) of 6.5%; they found that it should be harvested at an SSC of >8%, then refrigerated to obtain high-quality fruit (Fisk et al. 2006). Compared to “Ananasnaya,” “Cheongsan” hardy kiwifruit is harvested at 8% SSC to provide high-quality fruit to consumers (Han et al. 2019). For “Ananasnaya,” Fisk et al. (2006, 2008) examined how harvest maturity influences the effects of storage conditions (including temperature and relative humidity) and packaging on physicochemical, sensory, and nutritional characteristics. For climacteric fruit such as kiwifruit, tomato, and banana, exogenous ethylene treatment using ethylene or ethephon (2-chloroethyl phosphoric acid) enhances their flavor and color and

CONTACT Uk Lee rich26@korea.kr Division of Special Forest Resources, National Institute of Forest Science, Dongdaemun-gu, Republic of Korea

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development by accelerating ripening process (Saltveit 1999; Park et al. 2006). As Actinidia arguta is considered a type of climacteric fruit, ethylene could be a role to accelerate fruit ripening and softening (Wang et al. 2015). Therefore, artificial ripening with exogenous ethylene treatment could be helpful to produce high-quality fresh hardy kiwifruit than natural ripening under refrigeration or ambient temperature (Oh et al. 2014). After ripening, hardy kiwifruit can be eaten whole, as it is grape-sized, with smooth, thin and edible skin, unlike fuzzy kiwifruit. Although hardy kiwifruit generally requires ripening treatment before consumption, various studies have focused on its extending storage life and improving fruit quality rather than on improving the quality of ripe hardy kiwifruit.

“Autumn sense” is one of several newly developed hardy kiwifruit cultivars produced by breeding programs at the National Institute of Forest Science, South Korea; others include “Daesung,” “Saehan,” “Chilbo,” “Shingreen,” and “Charmgreen.” The mean fruit weight, SSC and total fruit yield per vine of “Autumn sense” are about 20 g, 19.5%Brix and 14–27 kg, respectively, which are bigger and higher value than other hardy kiwifruit cultivars (Oh et al. 2014; Kim et al. 2016). Its cultivation area is steadily increasing, especially in Kangwon Province, in northeastern South Korea. It can be cultivated early in the season, and can produce larger, better quality, and higher yield fruit than the other cultivars that are usually preferred by consumers. Harvesting at the appropriate time is necessary to achieve the optimal appearance and taste required by farmers and consumers. Therefore, determination of optimum harvest maturity plays a key role in the quality of hardy kiwifruit (Fisk et al. 2006). However, very little information is known about the ideal harvest maturity and actual time required to produce high-quality ripe “Autumn sense” hardy kiwifruit. Our objective was therefore to investigate the physiological parameters and sensory characteristics of unripe and ripe “Autumn sense,” and the effects of SSC-based harvest maturity.

Materials and methods

Plant material and exogenous ethylene treatment

The “Autumn sense” hardy kiwifruit (Actinidia arguta) were harvested from three-year old trees in a commercial orchard in Wonju-si, Gangwon-do, South Korea (Figure 1). The fruit were harvested at four different maturity stages (on 17, 21, 24, and 28 September 2020), with average SSC values of 6.2, 7.1, 8.1, and 9.1%, respectively. The fruit were selected randomly for harvesting, and were immediately transferred to the Laboratory of Forest Fruit Tree, Division of Special Forest Resources, National Institute of Forest Science, Suwon, Gyeonggi-do, South Korea. Sixty uniformly sized fruit were randomly divided into two groups; 30 for immediate measurement (at harvest) and 30 for ripening via exogenous ethylene treatment, before measurement.

Exogenous ethylene treatment used a commercial pouch-form ethylene agent (Fresh Ripe; Topfresh Co., Seoul, Korea). The fruit were packaged in a plastic container, and packed with a commercial ethylene agent inside an enclosed airtight plastic container (248 × 180 × 150 mm). The concentration inside the container was measured using gas chromatography (GC). The hardy kiwifruit were exposed to 1,000 μL·L⁻¹ for 24 h at room temperature. After 24 h, the container was opened, the ethylene agent was removed, and the fruit were stored for 48 h at ambient temperature to examine fully ripe fruit quality (Oh et al. 2014; Lim et al. 2017).

Fruit characteristics and quality attributes

Quality attributes were assessed at four different harvest maturity stages, at harvest and after ripening. To measure fresh weight, a digital scale (CUX-6200HX; CAS, Shimadzu Co., Kyoto, Japan) was used. Fruit length and diameter were measured using a digital Vernier caliper (CD-15APX, Mitutoyo, Kawasaki-shi, Japan). Flesh firmness was measured via a penetration test with a 5 mm diameter punch probe, to a depth of 5 mm, using a rheometer (CR-3000EX-S; Sun Scientific, Tokyo, Japan). The compression speed was 250 mm min⁻¹ at the center of the fruit, on a flat surface. The results are presented as the maximum penetration force, in Newtons (N).

The juice was squeezed by hand, using gauze to determine SSC and titratable acidity (TA). SSC was measured using a digital refractometer (PAL-1; ATAGO Co., Ltd., Tokyo, Japan). TA was evaluated
using a titratable acidity meter (GMK-835N; G-WON Hitech Co., Ltd., Seoul, Korea), and is expressed as the percentage of anhydrous citric acid, the dominant organic acid in *A. arguta* (Nishiyama et al. 2008). The SSC/TA ratio (SSC/TA) was calculated.

**Sensory evaluation**

Five trained panelists with normal smell and taste ability evaluated the ripe fruit samples. For food sample preparation, ripe fruit were cut into five cubes that were placed in paper cups and then presented randomly to panelists. One cube was placed in the mouth and chewed to evaluate fruit sensory preference on a five-point hedonic scale: 1, extremely dislikable; 2, dislikable; 3, moderately likable; 4, likable; 5, extremely likable, according to Fisk et al. (2008) with some modifications.

**Statistical analyses**

The experiments were designed to be completely randomized. Data were subjected to analysis of variance (ANOVA) to determine the effects of the main factors (harvest maturity stage and exogenous ethylene treatment) and their interactions (Version 18.0; SPSS, Inc., IL, USA). Duncan’s multiple range test was used to compare the means difference at \( p = 0.05 \). An analysis of Pearson correlations between fruit quality attributes at harvest and after exogenous ethylene treatment was performed using MetaboAnalyst 5.0 (Pang et al. 2021).

**Results and discussion**

**Fruit characteristics and quality attributes at harvest and after exogenous ethylene treatment**

The means of the fruit characteristics and quality attributes at harvest and after ethylene treatment are presented in Table 1. Fresh fruit weight ranged from 20.1 in H1 to 22.8 g in H4, immediately after harvest; the values were significantly highest in H3 and H4 than in H1 and H2, indicating that fruit weight increased during H2 and H3 stage. Fruit weight was affected by harvest maturity and ethylene treatment. Fruit length differs from each harvest maturity stage and ethylene treatment; also it is affected by their interactions. H3 and H4 had higher maximum and minimum diameters than H1 and H2. The perimeter gradually increased with harvest stages and significant difference occurred due to ethylene treatment.

The SSC, TA and SSC/TA ratio are important indicators for determining consumer fruit preference (Crisosto and Crisosto 2001, 2002). The overall sensory quality highly correlated with SSC and SSC/TA value in kiwifruit (Tilahun et al. 2020). SSC, TA, and SSC/TA were significantly influenced by harvest maturity, exogenous ethylene treatment and their interaction \((p < 0.001)\). The mean value of firmness differed significantly between the harvest stages, declining consistently from H1 (32.1 N) to H4 (25.1 N) \((p < 0.001)\). The firmness was drastically decreased 28.9 – 2.8 N due to ethylene treatment. Harvest maturity, ethylene treatment and their interaction highly affect to fruit firmness. SSC increased from 6.2% at H1 to 9.1% at H4, over 11 days. This is consistent with Fisk et al. (2006), who found that over the 15 day of the harvest period, the firmness immediately after harvesting of “Ananasnaya” decreased as SSC increased from 6.0% to 9.1%. Unlike firmness and SSC, TA increased from 0.8 in H1 to 1.1% in H3, then decreased to 0.9% in H4, in fruit immediately after harvest. The TA of “Skinny Green” hardy kiwifruit harvested on three different days after full bloom (DAFB) showed a similar trend (Oh et al. 2017), whereas that of “Ananasnaya” did not vary with maturity level (Fisk et al. 2006). The TA of “Bingo” hardy kiwifruit was increased 0.80 – 0.89% while the TA value of “Ananasnaya” decreased during two different maturity stage (Latocha et al. 2014). These results indicated that the trend of TA value during maturity vary depending on cultivars and harvest time of hardy kiwifruit.

The SSC/TA ratio is one way to assess the optimum harvesting time, fruit ripeness, and taste of several fruits (Zolfaghari et al. 2010). Immediately after harvest, the SSC/TA ratios gradually increased to 7.5, 7.9, 8.7, and 9.6, in H1, H2, H3, and H4, respectively; the value for H4 was significantly higher than for the other stages \((p < 0.001)\). This is because H4 had the highest SSC and lowest TA, indicating that the fruit was overripened on the vine because of the late harvest. Similarly, kiwifruit cultivars “Hayward,” “Haegum,” and “Hongyang” had higher SSC/TA values at 180 DAFB than at 160 and 170 DAFB (Choi et al. 2019). For the ethylene-treated fruit, SSC was 15.1%, 15.2%, 16.3%, and 16.4% in stages H1 to H4, respectively, and varied significantly with stage \((p < 0.001)\). According to Oh et al. (2014), “Autumn sense” treated with ethylene for 48 h had a firmness of 1.4 N and SSC of 17.4% at 20 °C, after four days of storage. TA is important factor that indicates fruit quality changes during storage (Islam et al. 2013; Cha et al. 2019). TA decreased significantly from 1.0% immediately
Table 1. Fruit characteristics and quality attributes of ‘Autumn sense’ hardy kiwifruit at harvest and after ripening with exogenous ethylene treatment, comparing four batches harvested at different maturity stages.

|                | H1          | H2          | H3          | H4          |
|----------------|-------------|-------------|-------------|-------------|
| Fruit weight (g) | 20.12b      | 20.39b      | 22.18a      | 22.81a      |
| Length (mm)     | 18.39c      | 19.55bc     | 21.18a      | 20.32ab     |
| Maximum diameter (mm) | 39.02a      | 36.77c      | 37.67b      | 39.79a      |
| Minimum diameter (mm) | 35.90b      | 36.24ab     | 35.76b      | 37.05b      |
| Perimeter (cm)  | 31.52ab     | 31.62a      | 32.64a      | 32.70a      |
| Firmness (N)    | 26.43a      | 25.97a      | 26.27a      | 26.36a      |
| SSC (%)         | 9.64a       | 9.46a       | 9.84a       | 9.60a       |
| TA (%)          | 2.67b       | 2.77b       | 2.67b       | 2.75b       |
| SSC/TA          | 3.14a       | 3.16a       | 3.10a       | 3.10a       |

Significance: *< 0.001, †< 0.001, ‡< 0.001, §< 0.001

Note: SSC: soluble solids content; TA: titratable acidity; SSC/TA: ratio of soluble solids content to titratable acidity; -/+ right after harvest at each stage; (+): after ethylene treatment; H: harvest stage based on soluble solids content value (H1 – H4 represented SSC value of 6.2%, 7.1%, 8.1% and 9.1%, respectively); E: exogenous ethylene treatment. Mean labeled with different superscript letters are significantly different at $p < 0.05$ (Duncan’s multiple range test).

Sensory evaluation

In sensory evaluation, H3 and H4 scored significantly higher ($p < 0.001$) for sweetness, sourness, and overall preference than H1 and H2 (Figure 2). Additionally, H3 had the highest overall preference (3.91) whereas the SSC/TA value showed highest in H4; because ripe fruit from H4 had an unlikable overripe taste. It indicates that SSC/TA value does not always reflect customer’s preference. Similarly, overall sensory quality of gold kiwifruit cv. Haegueum and red kiwifruit cv. Hongyang were higher for ripe fruit harvested at 170 DAFB than at 160 or 180 DAFB (Tilahun et al. 2020).

Correlations between fruit quality attributes at harvest and post-treatment

For kiwifruit, the sweet/sour balance strongly affects acceptability to consumers (Rossiter et al. 2000; Marsh et al. 2006), and consumer preference for fresh fruit is related to SSC, TA, and SSC/TA (Gorini et al. 1990). A heatmap of Pearson’s correlation coefficients was used to assess correlations between the fruit quality characteristics, for the four harvest stages, before and after ethylene treatment (Figure 3). The overall sensory preference positively correlated with SSC/TA at harvest ($r = 0.71$, $p < 0.01$), SSC ($r = 0.85$, $p < 0.001$) and sweetness of ripe fruit ($r = 0.98$, $p < 0.0001$), respectively. Similar with our results, Tilahun et al. (2020) reported that overall sensory of green, gold and red kiwifruit cultivar “Hayward,” “Haegueum” and “Hongyang” also positively correlated with TSS and SSC/TA. These results indicated that consumer usually preferred sweet taste and well-balanced sweet and sour taste.

Furthermore, fruit firmness at harvest strongly negatively correlated with SSC ($r = -0.91$, $p < 0.001$), minimum diameter ($r = -0.89$, $p < 0.001$), and fruit weight ($r = -0.85$, $p < 0.001$). SSC in freshly harvested fruit was positively correlated with the sweetness and sourness of ripened fruit. Moreover, the TA of freshly harvested fruit was positively correlated with the fruit weight ($r = 0.74$, $p < 0.01$), sweetness ($r = 0.63$, $p < 0.05$), and overall preference ($r = 0.71$, $p < 0.01$).
and SSC/TA ($r = 0.61, p < 0.05$) of the ripened fruit. For ripened fruit, SSC value was highly correlated with sweetness ($r = 0.89, p < 0.001$), sourness ($r = 0.83, p < 0.001$), and SSC/TA both at harvest ($r = 0.69, p < 0.05$) and after ripening ($r = 0.61, p < 0.05$). These results suggest that, together with SSC, TA and SSC/TA at harvest should be used to determine the optimal harvest maturity, to produce high-quality ready-to-eat hardy kiwifruit and to satisfy consumer taste preferences.

**Conclusion**

We investigated the effects of harvest maturity (harvest date) on “Autumn sense” hardy kiwifruit quality at harvest and after exogenous ethylene treatment, to determine the ideal harvest maturity stage. Harvest maturity highly affects the sensory characteristics of ripe hardy kiwifruit in terms of sweetness, sourness, and overall preference, and is therefore critical factor to produce high-quality hardy kiwifruit. Therefore, both SSC, TA, and SSC/TA values should be considered when determining the optimum harvest time for hardy kiwifruit. Fruit that were harvested with >8% SSC and >1% TA achieved better quality than only SSC value was considered. Future studies should examine ways to improve the application of optimal harvest maturity stages, and to develop precise criteria for harvest maturity for hardy kiwifruit orchards. These criteria should include DAFB, and the color changes of the fruit pericarp, parameters that are widely used to determine harvest maturity for various fruits.

**Disclosure statement**

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