RESEARCH ARTICLE https://doi.org/10.7235/HORT.20230053

Evaluation of Fruit Quality Characteristics in 'Irwin' Mango Grown via Forcing Cultivation in a Plastic Facility

W.M. Upeksha Darshani Wijethunga[1†], Mi Hee Shin[2†], L. Sugandhi Hirushika Jayasooriya[1], Gyeong Ho Kim[1], Kyoung Mi Park[3], Mi Geon Cheon[3], Sang Woo Choi[3], Hong Lim Kim[4], and Jin Gook Kim[1,2*]

[1]Division of Applied Life Science, Graduate School of Gyeongsang National University, Jinju 52828, Korea
[2]Institute of Agriculture and Life Sciences, Gyeongsang National University, Jinju 52828, Korea
[3]Department of Horticulture Research, Gyeongsangnam-do Agricultural Research and Extension Services, Jinju 52733, Korea
[4]Namhae Branch, National Institute of Horticultural and Herbal Science, Rural Development Administration, Namhae 52430, Korea

*Corresponding author: jgkim119@gnu.ac.kr

†These authors contributed equally to this work.

Abstract

The 'Irwin' mango is one of the most popular mango cultivars in South Korea, but the fruit perishes quickly after harvesting. Identifying the fruit characteristics is essential to improve the quality after harvest because they vary with the maturity stage. In this study, 'Irwin' mango samples were harvested as a whole and divided into five distinct maturity stage groups depending on the green color proportion of the total fruit skin (S1: Green > 50%, S2: Green 30–50%, S3: Green 20–30%, S4: Green 10–20%, S5: Green 0%). The physicochemical properties, in this case the chromaticity, firmness, soluble solids content (SSC), titratable acidity (TA), ethylene production rate, and respiration rate, were measured soon after harvesting the fruit. Consequently, the S1 and S5 stages showed higher and lower firmness and TA levels, respectively. Moreover, these values were significantly different in each stage. Along with the maturity stage, highest and lowest values in SSC were observed in S5 and S1; correspondingly, and the highest carbon dioxide and ethylene concentrations were observed in stages S5 and S4. With regard to chromaticity, no apparent variations were observed between the front and back sides of the fruit at every color value, though there were significant differences among the stages. By observing all of these quality characteristics, it can be concluded that fruit at the S3 and S4 stages are suitable for storage and are less preferred by consumers at harvest. In this case, the S5 stage is most suitable because the mangoes are at the ready-to-eat stage, more preferred by consumers, and can also be marketed at a higher price.

Additional key words: consumer preference, domestic mango, quality prediction, ripening, softening

Received: July 10, 2023
Revised: September 13, 2023
Accepted: September 26, 2023

HORTICULTURAL SCIENCE and TECHNOLOGY
41(6):617-633, 2023
URL: http://www.hst-j.org

pISSN : 1226-8763
eISSN : 2465-8588

This work was carried out with support from the "Cooperative Research Program for Agriculture Science and Technology Development (Project No. PJ0169532023)" Rural Development Administration, Republic of Korea.

Introduction

Mango (*Mangifera indica* L.) is one of the most popular tropical fruits around the globe, in high

demand, and is cultivated in well over 100 countries, with more than 65 of those producing more than 1,000 million metric tons (MT) annually (Mitra, 2016; Sánchez Aldana et al., 2021; Chung et al., 2023). Global mango production is primarily centered in Asia, at tropical and subtropical latitudes (Jha et al., 2006; Liu et al., 2013; Seehanam et al., 2022). According to recent metrics, the mango production volume of the globe was just over 57 million metric tons in 2021, showing a slight increase from around 56.69 million metric tons in 2020. When comparing the global production values for the previous five and ten years from 2021, the mango production volume increased by 20.5% and 45.2%, respectively (FAO, 2023). However, Asia produces approximately 76.5% of the world mango crop, followed by both South and North America and Africa with respective shares of 12.6 and 10.8%. India specifically produces an average of 15 MT of mangoes annually (Mitra, 2016). Mango is typically known as the "king of fruits" (Vilvert et al., 2022) owing to its sensory attributes desired by consumers, including its appealing color, delectable taste, and exotic flavor (Liu et al., 2013). These fruits are rich in bioactive substances, such as provitamin A, vitamin C, and carotenoids (Sánchez Aldana et al., 2021; Vilvert et al., 2022). In addition, mango has significant amounts of phenolic substances and ascorbic acid (Baloch and Bibi, 2012; Liu et al., 2013; Zahedi et al., 2019). In addition to direct consumption of approximately 80% of the harvested fruit, the remaining 20% is processed into value-added products (Sánchez Aldana et al., 2021), such as nectar, pickles, chutneys, slices, dried mango chips, and canned products (Nadeem et al., 2016; Mwaurah et al., 2020). The consumption of mangoes furnishes an outstanding source of antioxidants, as they are rich in bioactive compounds, thereby reducing the risk of developing certain types of cancer, improving lung function, slowing down aging, and reducing certain difficulties associated with diabetes (Han et al., 2016; Mandal et al., 2018; Eshetu et al., 2019). These facts highlight the need to improve consumer satisfaction and increase the demand for this fruit in foreign and domestic markets.

Mango is a highly perishable fruit owing to its climacteric nature (Kishore et al., 2023), characterized by a high respiration rate and ethylene production (Vilvert et al., 2022). Normally, mangoes reach respiration peaks on the third or fourth day after harvest at ambient temperatures (Eshetu et al., 2019). A series of biochemical reactions involved in the ripening process of mango accelerates the respiration rate, and ethylene production degrades polymers into simple compounds and softens the texture of the fruit. Furthermore, according to the storage condition, the post-harvest shelf life differs, ranging from four to eight days at ambient temperatures and two to three weeks in cold storage at a temperature of 13°C (Carrillo-Lopez et al., 2000; Eshetu et al., 2019). These factors hinder the long-distance commercial distribution of mangoes (Zahedi et al., 2019; Sánchez Aldana et al., 2021; Ali et al., 2022).

The physical, biochemical, and physiological characteristics of mango have been investigated to determine the ideal maturity stage for their harvest (Liu et al., 2013). Hence, numerous physicochemical characteristics have been investigated to develop accurate maturity indices. According to findings reported by Wanitchang et al. (2011), as mango fruit mature, the specific gravity rises and the titratable acidity decreases. In addition, the total sugars - glucose, sucrose, and fructose - are biochemical substances associated with fruit quality (Sitthiwong et al., 2005), all of which are important with regard to fruit development and sink strength. The mean soluble solids content (SSC) according to the total sugar level increases significantly with fruit maturity and ripening (Wanitchang et al., 2011). The fruit firmness of mangoes remains mostly consistent over the fruit development period and tends to decrease after maturity (Jha et al., 2006). Additionally, throughout the growth and maturation of mango fruit, starch accumulation represents another significant chemical change (Wongmetha et al., 2015).

Recently, mangoes have been cultivated in greenhouses throughout northeast Asia, including Korea. These mango trees

are grown in a vase shape with a low stem height, accomplished through branch pruning, owing to space limitations in greenhouses (Jung et al., 2018; Jung et al., 2022; Kishore et al., 2023). Among the several varieties of mango, the most well-known variety of mangoes grown commercially in South Korea, Japan, Taiwan, and Australia is the cultivar 'Irwin', often known as "Apple Mango". This cultivar was developed in 1949 from an open-pollinated seedling of Lippens in Florida, United States (Meurant et al., 1999). As part of the department's mango introduction and evaluation program, the variety was introduced to Australia in the late 1970s (Meurant et al., 1999; Shivashankara, 2006). These 'Irwin' mango trees are grown at small to medium heights; the fruit has a somewhat oval shape, the fruit length is approximately 11.5 − 13 cm, and the fruit diameter is about 8 − 9 cm (Lim et al., 2016). Mangoes have recently been grown in plastic greenhouses in the Gyeongnam area in Korea as such greenhouses offer an advantage when seeking to produce high-quality fruits given the weaker effect of the cold continental high pressure in winter. The location is also the warmest in the entire country besides Jeju Island due to the influence of temperate warm currents and plenty of sunshine (Han et al., 2016). In South Korea, the 'Irwin' mango variety was cultivated on Jeju Island in the early 2000s for the first time. From that time onwards, it's widely started to grow in Tongyeong in Gyeongnam, and recently in the Haman and Gimhae areas. In accordance with data from Gyeongsangnam-do Agricultural Research and Extension Services, as of 2022, there were 9.8 ha with 27 farms of apple mango production in Gyeongnam, up from 1 ha in 2010 on five farms.

The state of maturity at harvest determines the rate of ripening. In terms of marketing, assessing mango maturity at harvest is a crucial factor and remains an important concern, as the harvesting maturity factor is most relevant when predicting the eating quality (Wanitchang et al., 2011). Fruit harvested prematurely are of inferior quality because they have not fully ripened. On the other hand, harvesting when the fruit is too mature results in a limited shelf life and increased disease susceptibility. The main goal of maturity specifications is to prevent the harvest of immature fruit or to ensure the ripening and constant storage behavior for the specified distribution channel following harvest (Bartz and Brecht, 2002; Slaughter, 2009; Kienzle et al., 2011). The most common method for predicting the harvest date is to use the days after full bloom, based on the cultivar and the climatic conditions (Kienzle et al., 2011; Wanitchang et al., 2011). Mango growers use their cultivar-specific knowledge and expertise in relation to changes in peel color, size, and fruit shape, the emergence of lenticels, endocarp hardness (knocking on the fruit), the initiation of fruit drop, as well as the specific gravity to determine harvest dates and estimate maturity stages (Kienzle et al., 2011). These considerations are based on personal experience (Slaughter, 2009).

Many mango cultivators prefer this 'Irwin' cultivar because it ripens early and has an acceptable level of cold and disease resistance ability (Ueda et al., 2000). In addition, this cultivar has a very high level of consumer acceptance owing to its superior eating and fruit-keeping qualities. Its optimal harvesting maturity has been determined empirically to be approximately between 16 and 17 weeks (110 − 120 days) following flowering; otherwise, this is determined by the degree of fruit peel coloration and by the °Brix value of the fruit juice (Ueda et al., 2000). According to South Korea, this fruit is harvested commercially after dropping from the trees. At that stage, growers predict the suitable stage for maximizing consumer acceptability because they are in the ready-to-eat stage. However, farmers cannot predict whether this stage will match consumer preferences perfectly. In addition, the 'Irwin' mango cultivar is weak against anthracnose disease, meaning that problems in storage and transportation arise (Lim et al., 2016). More ripe fruits may be more susceptible to postharvest deterioration in storage. Hence, the detection of the optimal maturity stage considering the different aspects related to the farmers is critical. Therefore, in this study, alterations in the fruit quality characteristics of

'Irwin' mango fruits were observed at different maturity stages that were divided based on the green color proportion of the fruit skin. In so doing, this study aims to find the optimal maturity stage for the harvesting of 'Irwin' mangoes resulting in the ideal quality for consumers and that is also suitable considering the range of aspects at the commercial level.

Materials and Methods

Sample Preparation

The 'Irwin' mangoes utilized in this experiment were grown in a plastic greenhouse with heating in Haman, Gyeongsangnam-do, Republic of Korea. This experiment was carried out on June 1, 2022. One hundred and fifteen samples of 'Irwin' mango fruits were harvested as a whole and were then subjectively evaluated based on their green color proportion of the total fruit skin. These fruit were divided into five distinct maturity stages according to their skin color, as follows: Stage 1 (S1), Green > 50%; Stage 2 (S2), Green 30 − 50%; Stage 3 (S3), Green 20 − 30%; Stage 4 (S4), Green 10 − 20%; and Stage 5 (S5), Green 0% (Fig. 1). Each mango fruit, all uniformly matured in each maturity stage and free from external defects or disease, was chosen for the experiment. Around 23 fruits (biological replicates) were allocated for one treatment. Soon after they were harvested, they were covered with expanded polyethylene (EPE) fruit foam nets and packed evenly in plastic cartons. Subsequently, they were transported immediately to the laboratory in a fully air-conditioned state for further analysis. In this experiment, the fruit quality parameters were assessed only on the day of harvest.

Measurement of Physicochemical Properties

Soon after the 'Irwin' mango samples were taken to the Laboratory of Fruit Science at Gyeongsang National University, South Korea, they were washed with tap water in order to remove dirt and latex residue and were then wiped gently with paper towels. Subsequently, the physiochemical properties, in this case the chromaticity [L^*, a^*, b^*, a^*/b^*, chroma (C), and hue (h°)], soluble solids content (SSC), firmness, and titratable acidity (TA), were measured for 20 biological replicates (fruits); all aforementioned physicochemical properties were obtained from the same set of replicates separately for every maturity stage.

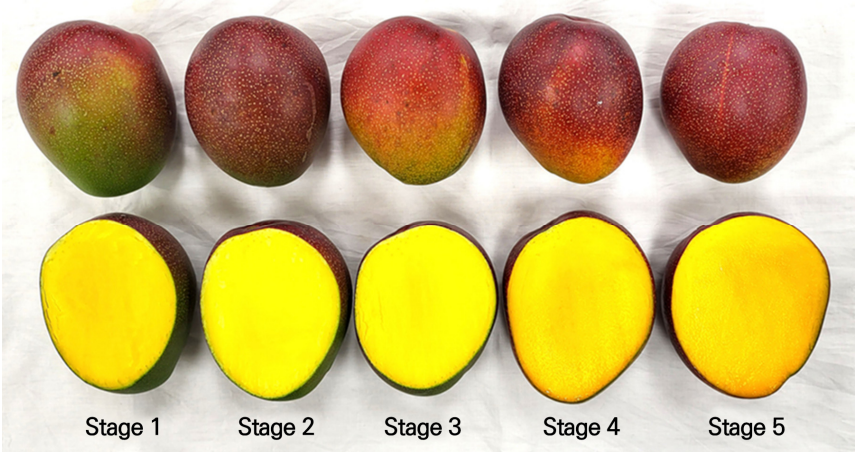

Fig. 1. Photographic images of the five maturity stages of 'Irwin' mango: S1 (Green > 50%), S2 (Green 30-50%), S3 (Green 20-30%), S4 (Green 10-20%), and S5 (Green 0%).

Measurement of chromaticity

The color values of the mango fruit samples for 20 biological replicates were measured using a portable colorimeter (CR-400, Konica Minolta Inc., Osaka, Japan). The L^*, a^*, and b^* chromaticity values were assessed on both the front and back sides of the fruit in all five sample sets, consisting of 20 fruits after white calibration was completed. These values were taken as a measurement of the fruit peel. The chroma (C) and hue (h°) values were then correspondingly computed using equations (1) and (2).

$$C = (a^{*2} + b^{*2})^{1/2} \quad (1)$$

$$h° = \tan^{-1}1(b^*/a^*) \quad (2)$$

Measurement of firmness

The firmness of 'Irwin' mango fruit was assessed for 20 biological replicates using a rheometer (CR-100, Sun Scientific Inc., Tokyo, Japan) equipped with an 8 mm round flat probe by compressing fruit flesh to a depth of 3 mm with a crosshead speed of 2 mm·S^{-1}. To assess the flesh firmness, each tested fruit was sliced into two longitudinal halves, and the firmness on the side with the seed was measured. The maximum force produced during the penetration was represented as the firmness in Newton values (N).

Measurement of the soluble solids content (SSC)

In this step, SSC measurements were taken for 20 biological replicates in the fleshy part of the center of the previously cut longitudinal slice without the seed. The square-shaped peeled mango flesh part was enfolded with a four-layer cheesecloth, squeezed, and the absorbance value was obtained using a hand refractometer (Pocket Refractometer, PAL-1, Atago Co. Ltd., Tokyo, Japan), calibrated in °Brix. The °Brix (%) range of the refractometer was 0 to 53% with a 0.1% °Brix resolution at room temperature, and it had a refractive index precision rate of ± 0.2%.

Measurement of titratable acidity (TA)

The TA was measured using a pH meter (BP3001, Trans Instruments, Jalan Kilang Barat, Singapore) for 20 biological replicates. Titration was carried out using 80 mL of distilled water diluted with 1 mL of fruit juice that had been extracted from the pulp. NaOH (0.1 mol·L^{-1}) was then added at a rate of 1 mL·min^{-1} to achieve a pH of 8.3 (Jang et al., 2022).

Determination of the Respiration Rate

Carbon dioxide production was determined for three biological replicates by weighing each fruit, sealing them in 2.1 L plastic boxes for 2 h, and injecting 1 mL of headspace gas into a gas chromatograph (GC-2014, Shimadzu Co., Ltd., Kyoto, Japan), as explained by Shivashankara et al. (2004) and Thammawong and Arakawa (2007). The respiration rate was measured using an SUS column (4 m × 2.2 mm) and a TCD detector with helium as the carrier gas under the following conditions: a column temperature of 35°C, an injector temperature of 250°C, and a detector temperature of 250°C. The respiration rate was then measured as an indicator of the CO_2 concentration, expressed as mg CO_2·kg^{-1}·hr^{-1}.

Determination of the Ethylene Production Rate

When determining the ethylene content for three biological replicates, 1 mL of the headspace gas was taken out, as described previously for CO_2 production, and was injected into a gas chromatograph. An ethylene analysis was carried out with a Porapak Q column and a TCD detector with helium as the carrier gas (GC-8A, Shimadzu Co. Ltd., Kyoto, Japan). The ethylene production rate was then measured and expressed as $\mu L \cdot kg^{-1} \cdot hr^{-1}$ (Thammawong and Arakawa, 2007; Wang et al., 2022).

Statistical Analysis

This experiment was set up using a completely randomized design (CRD). All data obtained were subjected to an analysis of variance (ANOVA) and analyzed statistically using JMP software (Version 16.1.0, SAS Institute, Cary, NC, USA). The effects of different maturity stages on various quality parameters were evaluated within the ANOVA. Significant differences among the mean values were assessed using Tukey's multiple range test ($p < 0.05$). All values are indicated as the mean value ± standard error (SE).

Results

Changes in Fruit Firmness

The firmness variation outcomes throughout the mango fruit maturity stages are shown in Fig. 2. The firmness value of the pericarp of the seeded side gradually decreased with the fruit maturity stage (Fig. 2) from 74.7 N to 7.3 N for stage 1 (S1) to stage 5 (S5), respectively. Among them, a definite decrement can be identified between stage 2 (S2) (62.8 N) and stage 3 (17.4 N). After the sudden decrease in fruit firmness in stage 2, the firmness values decreased moderately until S5. A significant difference ($p < 0.05$) was observed between every stage of maturity at the harvest date.

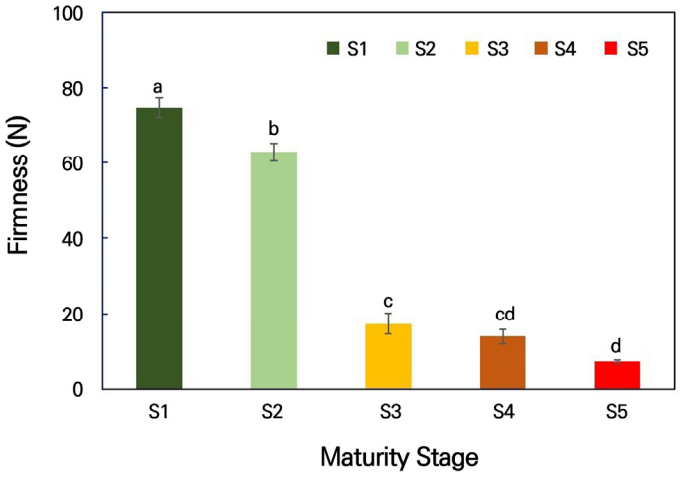

Fig. 2. Changes in firmness (N) of 'Irwin' mango among five maturity stages: S1 (Green > 50%), S2 (Green 30-50%), S3 (Green 20-30%), S4 (Green 10-20%), and S5 (Green 0%), where the letters denote significant differences according to Tukey's test at $p < 0.05$.

Changes in the Soluble Solids Content (SSC)

As Fig. 3 indicates, the SSC increased dramatically with the maturity stage. The significantly ($p < 0.05$) highest value for SSC was obtained in S5 as 14.5°Brix, while the significantly ($p < 0.05$) lowest value was obtained in S1 as 6.3°Brix. These SSC values were significantly different among each value obtained at different maturity stages. Nevertheless, the S1, S2, and S4, S5 stages did not show any significant differences ($p < 0.05$) for each stage on the experimental date.

Changes in Titratable Acidity (TA)

In our study, it was interesting to note that the TA value decreased exponentially with the maturity of the mangoes, as depicted in Fig. 4. The significantly highest TA value remains with the S1 and S2 stages, for which the corresponding

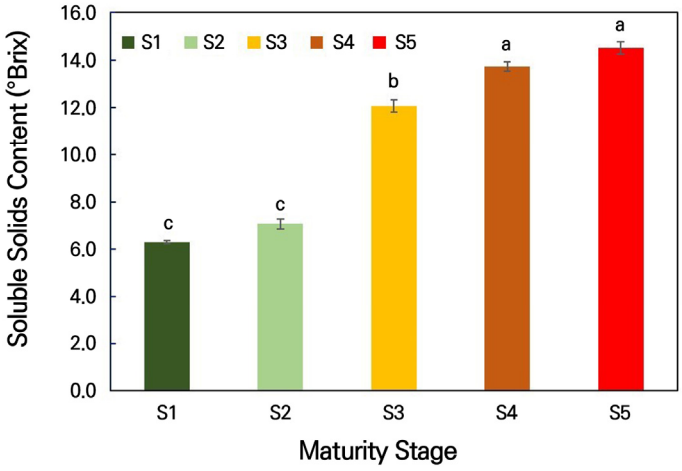

Fig. 3. Variations in the soluble solids content (°Brix) in 'Irwin' mango among five maturity stages: S1 (Green > 50%), S2 (Green 30-50%), S3 (Green 20-30%), S4 (Green 10-20%), and S5 (Green 0%), where the letters denote significant differences according to Tukey's test at $p < 0.05$.

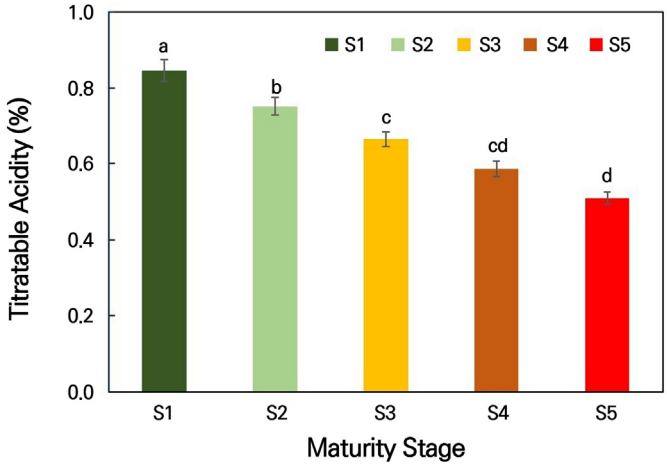

Fig. 4. Variations in titratable acidity (%) of 'Irwin' mango among five maturity stages: S1 (Green > 50%), S2 (Green 30-50%), S3 (Green 20-30%), S4 (Green 10-20%), and S5 (Green 0%), where the letters denote significant differences according to Tukey's test at $p < 0.05$.

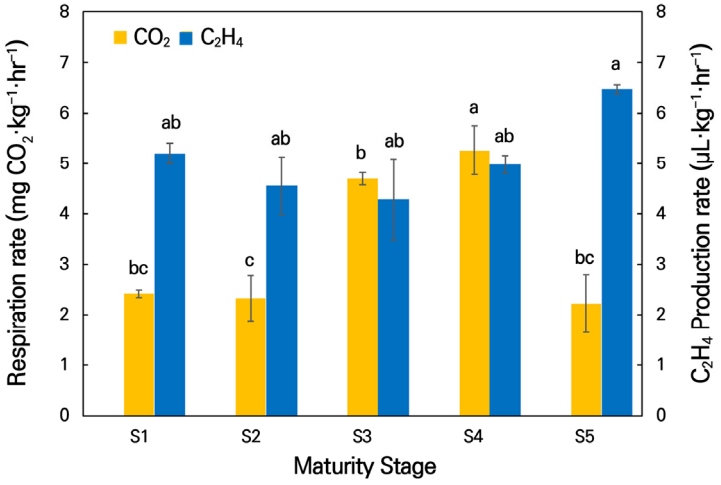

Fig. 5. Changes in the respiration rate and ethylene production rate of 'Irwin' mango among five maturity stages: S1 (Green > 50%), S2 (Green 30-50%), S3 (Green 20-30%), S4 (Green 10-20%), and S5 (Green 0%), where the letters denote significant differences according to Tukey's test at $p < 0.05$.

rates were 0.84% and 0.75%, while the lowest value was found at stage S5 with a TA of 0.51%. The maturity at harvest significantly ($p < 0.05$) affected the titratable acidity of the juice extracted from the pulp of 'Irwin' mangoes.

Changes in the Respiration Rate and Ethylene Production Rate

Changes in the respiration rate and ethylene production rate recorded as the mango fruit matured are shown in Fig. 5. Considering the respiration rate, the rates of S1 of 2.4 mg $CO_2 \cdot kg^{-1} \cdot hr^{-1}$, S2 of 2.3 mg $CO_2 \cdot kg^{-1} \cdot hr^{-1}$ and S5 of 2.2 mg $CO_2 \cdot kg^{-1} \cdot hr^{-1}$ were significantly ($p < 0.05$) similar, while the rates of S3 of 4.7 mg $CO_2 \cdot kg^{-1} \cdot hr^{-1}$ and S4 of 5.3 mg $CO_2 \cdot kg^{-1} \cdot hr^{-1}$ increased slightly and were approximately double that of S2. The highest peak respiration was obtained in S4 during maturation. The significantly lowest ($p < 0.05$) peak was found at S5.

Regarding the ethylene production rate, it decreased slightly with the S1 (Green > 50%) stage until the S3 (Green 20 − 30%) stage, at 5.2 $\mu L \cdot kg^{-1} \cdot hr^{-1}$ to 4.3 $\mu L \cdot kg^{-1} \cdot hr^{-1}$, respectively, with a rapid increase to S5, the fully ripened (Green 0%) stage, at 6.5 $\mu L \cdot kg^{-1} \cdot hr^{-1}$. The peak ethylene production rate was obtained at the S5 stage. In addition, significant differences ($p < 0.05$) were found among both respiration rates and ethylene production rates between the values obtained at different maturity stages.

Changes in Fruit Chromaticity

The surface color intensity of mangoes is one of the most important factors as regards external quality prediction and is a perfect maturity index (Ueda et al., 2000). As shown in Table 1, the L^* values (color lightness) of different maturity stages of 'Irwin' mangoes did not show a precisely significant type of variation on the opposite sides. The significantly higher ($p < 0.05$) values for the front and back sides were 41.1 and 44.1, respectively, at stages S4 and S3. Considering that a^* value represents red/greenness, a positive a^* value is for red color while a negative a^* value denotes green color (Ly et al., 2020; Perumal et al., 2021). In this experiment, the a^* color value increased throughout the maturity stages on the front sides of the mango fruit, while the back sides did not show any clear variation. The significantly ($p < 0.05$) lowest and

Table 1. Changes in L^*, a^*, and b^* color values and a^*/b^*, Chroma, and hue values of the front and back sides of the fruit in 'Irwin' mango with the five different maturity stages: S1 (Green > 50%), S2 (Green 30-50%), S3 (Green 20-30%), S4 (Green 10-20%), and S5 (Green 0%)

	Color											
Maturity	L^*		a^*		b^*		a^*/b^*		Chroma		Hue	
Stage	Front	Back	Front	Back	Front	Back	Front	Back	Front	Back	Front	Back
S1	37.1 bc	41.8 a	8.8 c	−1.1 c	12.0 b	18.5 bc	0.8 b	0.0 d	15.5 c	19.5 c	53.9 a	90.1 a[z]
S2	36.4 c	38.5 b	13.0 bc	9.1 b	10.2 b	14.3 c	1.3 a	0.7 bc	16.7 c	17.3 c	38.4 b	56.7 b
S3	39.5abc	44.1 a	17.6 ab	7.6 b	17.9 a	23.9 a	1.0 ab	0.4 cd	25.3 b	25.3 b	45.5 ab	45.5bc
S4	41.1 a	42.1 a	17.8 ab	20.8 a	19.8 a	22.3 ab	1.0 ab	1.0 b	28.2 ab	31.5 a	48.4 ab	47.6 bc
S5	40.2 ab	37.6 b	21.3 a	24.3 a	20.5 a	17.6 bc	1.2 ab	1.4 a	30.4 a	30.3 a	44.2 ab	36.1 c

[z]Letters denote significant differences according to Tukey's test at $p < 0.05$.

highest values were observed at 8.8 and 21.3 on the front sides at stages S1 and S5, respectively, and correspondingly at −1.1 and 24.3 on the back sides at S1 and S5 (Table 1). This negative value represents a greenish color on the fruit surface. The b^* value indicates the yellow/blue range; positive b^* values represent the yellow color, while a negative b^* denotes the blue color (Ly et al., 2020). According to Table 1, the b^* values obtained from the front sides of the fruit decreased until S2; this outcome was 10.2, which then increased gradually to 20.5 at stage S5. The significantly ($p < 0.05$) lowest b^* value of the front side was obtained at the S2 stage. Specifically, there was no exact variation of the b^* values for the back sides of the fruit, and all values were between 14.3 and 23.9 at S2 and S3, respectively. For a^*/b^*, no special variations were identified for the front side in any case. The values differed and were between 0.8 and 1.3. Although there is no specific pattern of changes, for the back side of the fruit, the a^*/b^* values were between 0.0 and 1.4 for S1 and S5, respectively. Also, significant ($p < 0.05$) difference was identified between the a^*/b^* values among the five different maturity stages. In addition, the chroma (C) measurements, which indicate the vividness of color (Perumal et al., 2021), were assessed, though these values also increased with the degree of fruit maturity on the front sides of the mangoes, from 15.5 to 30.4 correspondingly for S1 to S5, while the values on the back sides did not show any specific variation. The significantly ($p < 0.05$) highest (31.5) and lowest (17.3) values were obtained correspondingly from the S4 and S2 stages. The hue angle (h°) was applied to describe the perceived color; a hue angle of 0° corresponds to the color red, a hue angle of 60° to the color yellow, and a hue angle of 120° to the color green (Perumal et al., 2021). The average hue angle decreased gradually according to the maturity stage on the front and back sides of the fruit. Remarkably, these highest values near 120° indicate a greenish color of the skin at the S1 stage, which gradually turned yellowish and reddish with maturation. These facts were also confirmed with a visual inspection.

Discussion

Mango is a tropical fruit, a significant source of vitamins and minerals as well as an excellent resource that provides much income to farmers and exporters worldwide. Selecting an appropriate maturity stage to harvest mango fruits is likely to be critical because consumer acceptability when purchasing mainly depends on its outer appearance and flavor quality in addition to the keeping quality of the fruit. Usually, mangoes are harvested when they are at 60 − 70% maturity (Wei et al., 2021). Considering the cv. 'Irwin', the optimum maturity stage for harvesting has been practically assessed (imprecisely)

to be 16 − 17 weeks (110 − 120 days) after blooming. Generally, flower bud differentiation begins in 'Irwin' mangoes trees from November to December and flowering begins in early to mid-January (Chung et al., 2023). The 'Irwin' cultivar is commonly known as an early maturing variety as it is commonly harvested in early June, around June 8th to June 10th (Lim et al., 2016). As the fruit matures, the physicochemical and physiological properties vary widely depending on the mango cultivar being grown.

Changes in Fruit Firmness

Fruit texture is one of the primary attributes used to estimate the quality, storability, and shelf life of mango fruits (Wei et al., 2021; Vilvert et al., 2022). The decreasing pattern of flesh firmness during maturation, from S1 to S5 stages, reported in our study was similar to findings obtained by Ueda et al. (2000). They reported that the firmness measurement outcomes on the equator of the pericarp and the seed sides of 'Irwin' mango tended to decrease from 25.8 ± 5.0 to 1.8 ± 1.3 kg·cm^{-2} and 14.6 ± 2.2 to 2.0 ± 2.3 kg·cm^{-2}, respectively as maturity progressed. Even if there was a difference between the two sides at the beginning of maturity, the difference ultimately disappeared with maturation (Ueda et al., 2000). Although these values were somewhat lower than our findings, the change in firmness was generally similar to the present findings. Rooban et al. (2016) also reported that the firmness decreased gradually during the maturation process from 43.8 ± 2.19 to 18.5 ± 1.11 kgf·cm^{-2} between the immature and full ripening stages. During the ripening process, the lowest fruit firmness value was obtained in the over-ripened stage as 14.8 ± 1.03 kgf·cm^{-2}. According to another study of 'Irwin' mangoes grown in Korea by Lim et al. (2016), the average firmness value at harvest maturity of mango fruit was reported to be 2.3 ± 0.9 N.

A study focusing on the 'Kensington Pride' mango (Lalel et al., 2003; San, 2017) showed that the firmness of samples at different maturity stages did not change significantly ($p < 0.05$). In that study, the 'Kensington Pride' mango fruits, which were in both hard green and ripe stages, showed a fruit firmness value of 1.57 kg·cm^{-2} (Lalel et al., 2003), and the fruit firmness was not significantly ($p < 0.05$) affected by the maturity stage at harvest. On the other hand, our findings stand in contrast with the findings from these experiments. The reduction of the fruit firmness indicates cell wall changes related to cell-wall-hydrolyzing enzymes such as pectin methyl esterase (PME), pectate lyase, polygalacturonase (PG), and pectinase (Wongmetha et al., 2015; Mohamed et al., 2017). Ali et al. (2011) described that fruit softening during the maturation process may be related to declining fruit firmness; fruit softening is followed by cell wall disintegration, involving the solubilization of the insoluble forms of cellulose and pectin substances in the fruit cell wall during the process of fruit ripening following maturation (Verlent et al., 2005; Wongmetha et al., 2015; Perumal et al., 2021). Comparatively, the present findings found somewhat higher values for fruit firmness, even in the fully ripe stage 5 (S5). Hence, these fruits were even more firm than the 'Irwin' mango fruits tested in the study of Ueda et al. (2000), recorded a value 16 weeks after flowering of 5.8 ± 3.0 kg·cm^{-2}, and that by Lim et al. (2016), recorded a value of 2.3 ± 0.9 N, at the harvest stage. Hence, the S5 stage provides the preferable firmness value for harvesting, while the S4 stage is more suitable for storage.

Changes in the Soluble Solids Content (SSC)

The soluble solids content is a key maturity index used to estimate the nutritional value and the storability of fruits consisting of organic acids sugars and minerals (Wei et al., 2021). On the other hand, it is also related to fruit quality

attributes mainly responsible for fruit flavor, color, and microbial stability (Perumal et al., 2021). Essentially, in our study a dramatic increase was observed in the SSC values throughout the maturity period from S1 to S5. Owing to the complex metabolic processes in fruits, complex carbohydrates such as starches almost entirely start to hydrolyze into simple, water-soluble sugars, primarily glucose, fructose, and sucrose (Perumal et al., 2021; Vilvert et al., 2022). These sugars are the main factors affecting the sweetness and the taste of the fruits, as indicated by the increased SSC values (Vilvert et al., 2022). However, these intricate metabolic activities in mango fruits can accelerate with the maturation and ripening processes, eventually causing an increment in the SSC value for 'Irwin' mango fruits during the maturity stages, from the immature S1 (Green > 50%) stage to the fully ripened S5 (Green 0%) stage.

According to Wanitchang et al. (2011), the SSC values of the 'Nam Dokmai' mango increases progressively during its development; at the immature stage it ranges from 6.60 to 8.12°Brix, increasing at a slower rate at the mature stage from 8.14 to 8.80°Brix as the fruit matures. At the end of maturation, SSC increases more quickly towards the over-mature stage and then finally decreases. On the other hand, as Ueda et al. (2000) explained, their samples I, II, and III of 'Irwin' mangoes grown in Japan, harvested 10, 13, and 16 weeks after blooming, had SSC (°Brix) values that rose slightly, at 6.3, 9.2, and 9.8, respectively. The soluble solids of the fruit harvested at 19 weeks after blooming rapidly then increased to 17.3, corresponding somewhat to the 16.6°Brix value of physiologically over-matured 'Irwin' mangoes (Ueda et al., 2000). Nevertheless, another study involving the 'Irwin' cultivar obtained SSC values of approximately 14.2°Brix at the harvest maturity stage (Sasaki and Utsunomiya, 2002). Moreover, as Lim et al. (2016) reported, the 'Irwin' mango fruits cultivated in Korea show a °Brix value of 14.7 at harvest maturity, though Lalel et al. (2003) reported that SSC changes in 'Kensington Pride' mango fruits were not significantly affected by the maturity stage. Also, at the hard green stage, the SSC was about 14.9 while at the ripe stage, it was about 15.3. Hence, these findings are dissimilar to those here.

The SSC values in mango cultivars differ depending on variety (Lim et al., 2016). As the information above explains, the average SSC value of 'Irwin' mangoes at harvest is around 15°Brix, comparatively lower than those of 'Kensington Pride' and 'Keit' mangoes and higher than that of cultivars such as 'Nam Dokmai' (Lalel et al., 2003; Wanitchang et al., 2011; Lim et al., 2016). However, the SSC values at the harvest maturity in most 'Irwin' mangoes grown in Japan are similar to the 'Irwin' cultivars grown in Korea (Lim et al., 2016). According to the present study, the value obtained for stage 5, the fully ripened stage, was 14.5°Brix, significantly lower than 16.6°Brix, showing that stage 5 is not an over-mature stage and that it is a counterpart to the average SSC value of 'Irwin' mangoes obtained at harvesting maturity. Hence, S5 stage in the present study is preferred to the harvest stage, as at that point the fruits have good flavor quality, and the S4 stage with comparatively lower SSC values is preferable for storage because the SSC value can be increased further during the ripening stage in the storage condition. On the other hand, Jimenez et al. (2011) and Rooban et al. (2016) reported similar SSC values.

Changes in Titratable Acidity (TA)

Titratable acidity refers to one of the most significant sensory characteristics utilized in fruit quality measurements as maturity and ripening indices (Wei et al., 2021; Vilvert et al., 2022). Mangoes mainly consist of organic acids, most abundantly citric acid and malic acid (Wei et al., 2021; Vilvert et al., 2022). TA is also a main constituent influencing the flavor quality of mangoes, medium acidity, and high sugar; SSC is a favorable attribute related to the desired quality and flavor for customers (Wei et al., 2021). In accordance with the present findings, the TA content was found to be 0.8% at

the first maturity stage, after which it decreased dramatically throughout the maturity stages. According to Rooban et al. (2016), the TA contents of mangoes decreased with the maturity stage from 2.6 to 1.4%, from the immature stage to the over-mature stage. Compared to these values, those in the present study were considerably lower. The findings of Lalel et al. (2003) are generally similar to present observations, as in this study, the TA contents gradually decreased from 0.77 to 0.58% from the hard green to the ripe stage.

Another study of 'Nam Dokmai' mangoes (Wanitchang et al., 2011) showed that the TA content dropped gradually over the period of development (from 3.29% to 2.24%) and continued at a similar rate throughout maturity until it stabilized to 1.33% at 115 days after fruit set (over-mature stage). On the other hand, results reported by Wongmetha et al. (2015) reveal that the TA content in mangoes increases at the immature stage, dropping sharply towards the end of maturity. These findings are in contrast with those here. Generally, immature fruits have higher levels of acids that decrease as the fruits mature, up to the point of fruit senescence following fruit ripening (Wongmetha et al., 2015). An increase in the TA content in mangoes indicates the formation of organic acids during the fruit maturity stages. The acidity of all mangoes decreases with maturation due to the breakdown of starch molecules into more sugars (gluconeogenesis), which lowers the acidity of the fruit (Shafique et al., 2006; Wongmetha et al., 2015). In addition, the gradual decrease in the TA content of mango fruits may be due to the conversion of acids into sugars by certain physiological and biochemical changes (Shafique et al., 2006; Wongmetha et al., 2015). It can be speculated that climacteric respiration is an enzymatic process responsible for the decrease in the TA level during the mango ripening stages because organic acids are a substrate for fruit respiration (Nordey et al., 2016; Nia et al., 2021).

According to a parallel study of 'Irwin' mango grown in Korea by Lim et al. (2016), the TA value obtained was around 0.2% upon harvesting maturity. Comparatively, the 0.5% TA content obtained in our study at the S5 fully ripened stage is quite similar to this value. Because there is no major difference between 0.2% and 0.5%, most likely this stage was less acidic and thus meets the preferable consumer standard regarding this metric. Generally, when in storage, the TA contents decrease further with an increase in the storage time due to further ripening and senescence processes, the respiration process, the use of organic acid to conserve energy by fruit cells, and in some cases excessive fungal growth on the fruits caused by poor sanitary conditions (Nia et al., 2021). Hence, the S3 and S4 stages are deemed to be suitable for storage conditions.

Changes in the Respiration Rate and Ethylene Production Rate

As mangoes ripen and senescence occurs, the ethylene production rate (autocatalytic) increases, the peel carotenoids degrade, respiration increases, and softening occurs (Wongmetha et al., 2012). Considering earlier findings, Lalel et al. (2003) reported that mature fruits of 'Kensington Pride' mangoes harvested at the hard-mature green stage exhibited the typical climacteric pattern for respiration and ethylene production rates, indicating that the mangoes harvested at hard-mature green stages are in a pre-climacteric stage and that fruits at other stages do not exhibit an increase in the ethylene production rate or respiration rate; i.e., they are in a post-climacteric stage. According to evidence pertaining to the 'Alphonso' variety presented by Lakshminarayana et al. (1970), the respiration rates immediately after fruit set are high, but they decrease by the third week and then increase again, reaching the peak value in the fourth week. Because the respiration rates and ethylene production rates were evaluated only on the harvest day in the present study, it is difficult to explain further the climacteric patterns of different stages. However, the increased respiration rates in the middle stages

(S3 and S4) of maturity indicate the onset of the climacteric rise of the 'Irwin' mango fruits entering the ripening phase. The sudden drop in the respiration rate at the S5 stage indicates that the fruit has completely entered the ripening phase by this stage according to our study.

On the other hand, Wongmetha et al. (2012, 2015) also reported that the 50 DAA (days after anthesis) stage during maturation showed a higher respiration rate and higher ethylene production rate compared to other stages in cv. Jinhwang and cv. Irwin. Although the initial maturity stage of the 'Irwin' mangoes used in present study was quite different from those in the aforementioned studies, similar results were obtained for both respiration rates and ethylene production rates. These results provide evidence that the first stages of maturity (S1 and S2) are pre-climacteric stage while the late stages (S4 and S5) are post-climacteric stages. High respiration and ethylene production rates in immature mangoes occur due to vigorous fruit growth during those stages (Tadesse et al., 2002). In this experiment, however, decreased respiration rates were found at the early stages of mango growth because the physiological activities and active growth were somewhat completed in stage 1.

Fruit ripening is known as an oxidative phenomenon that requires the throughput of active oxygen species such as H_2O_2 and superoxide anions (Huang et al., 2007). These active oxygen species are most apparent during ripening and cause increased lipid peroxidation and protein oxidation products primarily influencing chilling injuries most commonly in mangoes (Han et al., 2016; Rosalie et al., 2018). Owing to the loss of a heat-labile and non-dialyzable inhibitor of these enzymes, the catalase and peroxidase activities were shown to rise significantly in mangoes along with the ethylene evolution and respiratory climacteric activities (Wongmetha et al., 2012). These antioxidant enzymes are responsible for scavenging active oxygen species, and the enzyme activity is comparatively high in fully mature fruits compared to half mature and immature fruits (Rosalie et al., 2018). Hence, ethylene in mango fruit inactivates the inhibitors of these enzymes, even in the pre-climacteric stages (Rosalie et al., 2018).

Changes in Fruit Chromaticity

Fruit color is a very important trait in mangoes and can be applied to assess consumer perception when purchasing fruits (Perumal et al., 2021). As Lalel et al. (2003) indicated, the skin of fully ripe 'Kensington Pride' mango fruits is noticeably lighter than the skin of the ripe fruits obtained at other maturity stages. There was no significant difference in the b^* or chroma values of the skin of any fruit, regardless of the maturity stage at harvest; however, the a^* value was significantly ($p < 0.05$) lower in the skin of ripened fruits collected at the hard-green mature stage. When compared to fruit collected at various stages of maturity, mature fruit picked at the deep green stage had a significantly ($p < 0.05$) higher skin hue angle. Except for the b^* value and chroma value, other color values concurred with those here. In addition, Wanitchang et al. (2011) reported that the 'Nam Dokmai' mango appeared lighter throughout the immature stage. Afterward, an increase in the L^* value took place at a slower rate, and the yellow color of the skin, which is denoted by the b^* value, decreased continuously. The green color on the fruit surface decreased gradually as the a^* value increased. One of the most obvious indications of fruit maturing and ripening is the general loss of green color on the fruit skin (Wanitchang et al., 2011). Hence, except for the variation in the b^* value, the changes in the other color values are in good agreement with those in the present study. Similar results were reported in another study of 'Irwin' mango as well (Ueda et al., 2000).

When compared to fruits harvested at five different maturity stages, mature fruits picked at the S1 stage (Green > 50%) showed lower rates of chlorophyll degradation (low a^* value), lower total sugar levels, and reduced sugar levels as well as

higher acid contents (Table 1, Figs. 3 and 4; Lalel et al., 2003). At this stage, the ripening enzymes responsible for starch hydrolysis, acid catabolism, and skin color changes have not yet been fully synthesized and activated (Lalel et al., 2003). Generally, in the 'Irwin' mango cultivar, the green color of immature mangoes becomes reddish-yellow with maturation, later changing to a remarkable dark red color at the fully mature stage (ready-to-eat stage) (Fig. 1). This identical red color of 'Irwin' mangoes could be caused by anthocyanin in the fruit skin. In addition, the green color of immature mangoes tended to decrease, becoming reddish-yellow with chlorophyll degradation and the increased accumulation of anthocyanin and carotenoids during fruit maturation and ripening (Ma et al., 2018; Li et al., 2019). Hence, the slight increase in the b^* values in the current study may have led to this observation in the 'Irwin' mango. As the beginning of the climacteric peak of mango fruits, chlorophyll degrades with carotenoid biosynthesis as a result of fruit ripening. Higher respiration and ethylene evolution rates and faster ripening caused by increased PME and PG enzyme activity levels may contribute to the presence of more carotenoids in mango fruits (Meena and Asrey, 2018).

According to the aforementioned findings, the changes in the various physical attributes and contents of certain critical compounds that influence the quality of 'Irwin' mangoes cultivated in plastic greenhouse environments with heating appear to occur most significantly between S3 and S4. Hence, the physical and chemical characteristics of mangoes are altered during this period, or upon growth the fruit enters senescence after maturing (Ueda et al., 2000).

Conclusion

The ripening process and alterations in fruit quality levels are significantly impacted by the maturity stage at harvest. Harvesting mango during the 0% green-colored S5 stage appears to result in the best quality for eating, as at this point they have significantly highest SSC levels, preferable color values, and the lowest TA and firmness levels. The 20−30% green-colored (S3) and the 10−20% green-colored (S4) stages are suitable for storage given that they have somewhat low physicochemical and physiological characteristic value compared to those at the S5 stage, making them less consumer preferable at harvest. 'Irwin' mango cultivation is currently trending most strongly among South Korean mango farmers, and these fruits are usually marketed as mangoes after dropping from the trees. In this case, finding a suitable stage by subjectively observing the fruit skin may be the most convenient and easiest method for farmers, as they can easily distinguish the most preferable stages of mangoes most appropriate depending on the marketing path and can bring in considerable income. Since the 'Irwin' mangoes are a cultivar that matures early, the lack of diversified shipping times may cause price decreases and the fruit eventually may not meet consumers' perfect preferences. Studying the fruit characteristics at different maturity stages is beneficial for identifying the optimal stage for harvesting mangoes. Therefore, findings here address this issue regarding mango farmers and exporters in the South Korean mango industry. Given that our findings augment other studies of consumer-acceptable fruit quality characteristics, it is proven that this strategy is a more accurate validation for determining optimal maturity levels for harvesting 'Irwin' mango as opposed to the personal experience of farmers. In addition, these results provide farmers with the potential to reduce losses during the harvesting process, to enhance consumer preferences for 'Irwin' mangoes, and to increase their commercial profits for mango production.

Literature Cited

Ali A, Muhammad MTM, Sijam K, Siddiqui Y (2011) Effect of chitosan coatings on the physicochemical characteristics of Eksotika II papaya (*Carica papaya* L.) fruit during cold storage. Food Chem 124:620-626. doi:10.1016/j.foodchem.2010.06.085

Ali S, Anjum MA, Khan AS, Nawaz A, Ejaz S, Khaliq G, Iqbal S, Ullah S, Rehman RNU, et al. (2022) Carboxymethyl cellulose coating delays ripening of harvested mango fruits by regulating softening enzymes activities. Food Chem 380:131804. doi:10.1016/j.foodchem.2021.131804

Baloch MK, Bibi F (2012) Effect of harvesting and storage conditions on the post harvest quality and shelf life of mango (*Mangifera indica* L.) fruit. S Afr J Bot 83:109-116. doi:10.1016/j.sajb.2012.08.001

Bartz JA, Brecht JK (2002) Post-harvest physiology and pathology of vegetables. eds. Ed 2, Vol 123. Crc Press, Florida. doi:10.1201/9780203910092

Carrillo-Lopez A, Ramirez-Bustamante F, Valdez-Torres JB, Rojas-Villegas R, Yahia EM (2000) Ripening and quality changes in mango fruit as affected by coating with an edible film. J Food Qual 23:479-486. doi:10.1111/j.1745-4557.2000.tb00573.x

Chung SW, Jang YJ, Lim CK, Kim S, Kim SC (2023) Effects of 1-Naphthaleneacetic acid on the panicle and fruit characteristics of 'Irwin' mango trees. Hortic Sci Technol 41:361-369. doi:10.7235/HORT.20230033

Eshetu A, Ibrahim AM, Forsido SF, Kuyu CG (2019) Effect of beeswax and chitosan treatments on quality and shelf life of selected mango (*Mangifera indica* L.) cultivars. Heliyon 5:01116. doi:10.1016/j.heliyon.2018.e01116

Food and Agriculture Organization (FAO) (2023) Mango production worldwide from 2000 to 2021 (in million metric tons). Statista, Statista Inc. Available via: https://www.statista.com/statistics/577951/world-mango-production/. Accessed 20 August 2023

Han SH, Kim JS, Toshiaki T, Teruya Y, Moromizato I, Lim CK (2016) Comparison of the fruit qualities, the free radical scavenging activities and mangiferin content of the mango, cv. Irwin cultivated in Jeju and Okinawa. Hortic Sci Technol 34:634-643. doi:10.12972/kjhst.20160065

Huang R, Xia R, Hu L, Lu Y, Wang M (2007) Antioxidant activity and oxygen-scavenging system in orange pulp during fruit ripening and maturation. Sci Hortic 113:166-172. doi:10.1016/j.scienta.2007.03.010

Jang KE, Kim G, Shin MH, Cho JG, Jeong JH, Lee SK, Kang D, Kim JG (2022) Field Application of a Vis/NIR Hyperspectral Imaging System for Nondestructive Evaluation of Physicochemical Properties in 'Madoka' Peaches. Plants 11:2327. doi:10.3390/plants11172327

Jha SN, Kingsly ARP, Chopra S (2006) Physical and mechanical properties of mango during growth and storage for determination of maturity. J Food Eng 72:73-76. doi:10.1016/j.jfoodeng.2004.11.020

Jimenez AM, Sierra CA, Rodriguez-Pulido FJ, Gonzalez-Miret ML, Heredia FL, Osorio C (2011) Physicochemical characterisation of gulupa (*Passiflora edulis* Sims. fo edulis) fruit from Colombia during the ripening. Food Res Int 44:1912-1918. doi:10.1016/j.foodres.2010.11.007

Jung DH, Hwang I, Son JE (2022) Three-dimensional estimation of greenhouse-grown mango photosynthesis with different CO_2 enrichment heights. Hortic Environ Biotechnol 63:823-834. doi:10.1007/s13580-022-00453-3

Jung DH, Lee JW, Kang WH, Hwang IH, Son JE (2018) Estimation of whole plant photosynthetic rate of irwin mango under artificial and natural lights using a three-dimensional plant model and ray-tracing. Int J Mol Sci 19:152. doi:10.3390/ijms19010152

Kienzle S, Sruamsiri P, Carle R, Sirisakulwat S, Spreer W, Neidhart S (2011) Harvest maturity specification for mango fruit (*Mangifera indica* L. 'Chok Anan') in regard to long supply chains. Post-harvest Biol Technol 61:41-55. doi:10.1016/j.postharvbio.2011.01.015

Kishore K, Singh HS, Nath V, Baig MJ, Murthy DS, Acharya GC, Behera S (2023) Influence of canopy architecture on photosynthetic parameters and fruit quality of mango in tropical region of India. Hortic Environ Biotechnol 64:557-569. doi:10.1007/s13580-022-00500-z

Lakshminarayana S, Subhadra NV, Subramanyam H (1970) Some aspects of developmental physiology of the mango fruit. J Hortic Sci Biotechnol 45:133-142. doi:10.1080/00221589.1970.11514339

Lalel HJD, Singh Z, Tan SC (2003) Maturity stage at harvest affects fruit ripening, quality and biosynthesis of aroma volatile compounds in "Kensington Pride" mango. J Hortic Sci Biotechnol 78:225-233. doi:10.1080/14620316.2003.11511610

Li D, Zhang X, Li L, Aghdam MS, Wei X, Liu J, Xu Y, Luo Z (2019) Elevated CO_2 delayed the chlorophyll degradation and anthocyanin accumulation in postharvest strawberry fruit. Food Chem 285:163-170. doi:10.1016/j.foodchem.2019.01.150

Lim C, Moon D, Seong K, Kim C, Jung Y, Park K, Song S (2016) Selection of mango (*Magnifera indica* L.) cultivars suitable for fruit production from greenhouse condition in Jeju Island, Korea. Korean J Breed Sci 48:126-132. doi:10.9787/KJBS.2016.48.2.126

Liu FX, Fu SF, Bi XF, Chen F, Liao XJ, Hu XS, Wu JH (2013) Physico-chemical and antioxidant properties of four mango (*Mangifera indica* L.) cultivars in China. Food Chem 138:396-405. doi:10.1016/j.foodchem.2012.09.111

Ly BCK, EDyer EB, Feig JL, Chien AL, Del Bino S (2020) Research techniques made simple: cutaneous colorimetry: a reliable technique for objective skin color measurement. J Invest Dermatol 140:3-12. doi:10.1016/j.jid.2019.11.003

Ma G, Zhang L, Yungyuen W, Sato Y, Furuya T, Yahata M, Yamawaki K, Kato M (2018) Accumulation of carotenoids in a novel citrus cultivar 'Seinannohikari' during the fruit maturation. Plant Physiol Biochem 129:349-356. doi:10.1016/j.plaphy.2018.06.015

Mandal D, Sailo L, Hazarika TK, Shukla AC (2018) Effect of edible coating on shelf life and quality of local mango cv. Rangkuai of Mizoram. Res Crops 19:419-424

Meena NK, Asrey R (2018) Tree age affects physicochemical, functional quality and storability of Amrapali mango (*Mangifera indica* L.) fruits. J Sci Food Agric 98:3255-3262. doi:10.1002/jsfa.8828

Meurant N, Holmes R, MacLeod N, Fullelove G, Bally ISE, Kernot I (1999) Mango Information Kit. Agrilink, your growing guide to better

farming guide. Manual. Agrilink Series QAL9903. Department of Primary Industries, Queensland Horticulture Institute, Brisbane, Queensland

Mitra SK (2016) Mango production in the world-present situation and future prospect. Acta Hortic 1111:287-295. doi:10.17660/ActaHortic.2016.1111.41

Mohamed MAA, El-Khalek AFA, Elmehrat HG (2017) Preharvest applications of potassium silicate, chitosan and calcium chloride to improve mango cv. 'Zibda' fruit quality and storability. Egypt J Hortic 44:17-32. doi:10.21608/ejoh.2017.949.1001

Mwaurah PW, Kumar S, Kumar N, Panghal A, Attkan AK, Singh VK, Garg MK (2020) Physicochemical characteristics, bioactive compounds and industrial applications of mango kernel and its products: A review. Compr Rev Food Sci Food Saf 19:2421-2446. doi:10.1111/1541-4337.12598

Nadeem M, Imran M, Khalique A (2016) Promising features of mango (*Mangifera indica* L.) kernel oil: a review. J Food Sci Technol 53:2185-2195. doi:10.1007/s13197-015-2166-8

Nia AE, Taghipour S, Siahmansour S (2021) Pre-harvest application of chitosan and postharvest Aloe vera gel coating enhances quality of table grape (*Vitis vinifera* L. cv. 'Yaghouti') during postharvest period. Food Chem 347:129012. doi:10.1016/j.foodchem.2021.129012

Nordey T, Léchaudel M, Génard M, Joas J (2016) Factors affecting ethylene and carbon dioxide concentrations during ripening: Incidence on final dry matter, total soluble solids content and acidity of mango fruit. J Plant Physiol 196:70-78. doi:10.1016/j.jplph.2016.03.008

Perumal AB, Nambiar RB, Sellamuthu PS, Emmanuel RS (2021) Use of modified atmosphere packaging combined with essential oils for prolonging post-harvest shelf life of mango (cv. Banganapalli and cv. Totapuri). LWT 148:111662. doi:10.1016/j.lwt.2021.111662

Rooban R, Shanmugam M, Venkatesan T, Tamilmani C (2016) Physiochemical changes during different stages of fruit ripening of climacteric fruit of mango (*Mangifera indica* L.) and non-climacteric of fruit cashew apple (*Anacardium occidentale* L.). J Appl Adv Res 1:53-8. doi:10.21839/jaar.2016.v1i2.27

Rosalie R, Léchaudel M, Dhuique-Mayer C, Dufossé L, Joas J (2018) Antioxidant and enzymatic responses to oxidative stress induced by cold temperature storage and ripening in mango (*Mangifera indica* L. cv. 'Cogshall') in relation to carotenoid content. J Plant Physiol 224:75-85. doi:10.1016/j.jplph.2018.03.011

San AT (2017) Lenticel discolouration, under-skin browning and resin canal disorder in Australian mango fruit cultivars. PhD Thesis, School of Agriculture and Food Sciences, The University of Queensland. doi:10.14264/uql.2017.605

Sánchez Aldana D, Aguilar CN, Contreras-Esquivel JC, Souza MP, Carneiro-da-Cunha MdG, Nevárez-Moorillón GV (2021) Use of a Mexican lime (*Citrus aurantifolia* Swingle) edible coating to preserve minimally processed mango (Mangifera indica L). Hortic Environ Biotechnol 62:765-775. doi:10.1007/s13580-021-00347-w

Sasaki K, Utsunomiya N (2002) Effect of fruit thinning on fruit growth and profitability in 'Irwin' mango cultivation under greenhouse. Japanese J Trop Agric 46:295-297A

Seehanam P, Chaiya P, Theanjumpol P, Tiyayon C, Ruangwong O, Pankasemsuk T, Nakano K, Ohashi S, Maniwara P (2022) Internal disorder evaluation of 'Namdokmai Sithong' mango by near infrared spectroscopy. Hortic Environ Biotechnol 63:665-675. doi:10.1007/s13580-022-00435-5

Shafique MZ, Ibrahim M, Helali MOH, Biswas SK (2006) Studies on the physiological and biochemical composition of different mango cultivars at various maturity levels. J Sci Ind Res 41:101-108. doi:10.3329/bjsir.v41i1.279

Shivashankara K, Isobe S, Al-Haq MI, Takenaka M, Shiina T (2004). Fruit antioxidant activity, ascorbic acid, total phenol, quercetin, and carotene of Irwin mango fruits stored at low temperature after high electric field pretreatment. J Agric Food Chem 52:1281-1286. doi:10.1021/jf030243l

Shivashankara KS (2006) Volatile aromatic constituents of tree ripened and mature green 'Irwin' mango fruits during low temperature storage. J Jpn Soc Hortic Sci 75:209-212. doi:10.2503/jjshs.75.209

Sitthiwong K, Matsui T, Okuda N, Suzuki H (2005) Changes in carbohydrate content and the activities of acid invertase, sucrose synthase, and sucrose phosphate synthase in vegetable soybean during fruit development. Asian J Plant Sci. doi:10.3923/ajps.2005.684.690

Slaughter DC (2009) Nondestructive Maturity Assessment Methods for Mango. Agric Eng 18:999-1005

Tadesse T, Hewett EW, Nichols MA, Fisher KJ (2002) Changes in physicochemical attributes of sweet pepper cv. Domino during fruit growth and development. Sci Hortic 93:91-103. doi:10.1016/S0304-4238(01)00317-X

Thammawong M, Arakawa O (2007) Starch degradation of detached apple fruit in relation to ripening and ethylene. J Jpn Soc Hortic 76:345-350. doi:10.2503/jjshs.76.345

Ueda M, Sasaki K, Utsunomiya N, Inaba K, Shimabayashi Y (2000) Changes in physical and chemical properties during maturation of mango fruit (*Mangifera indica* L. 'Irwin') cultured in a plastic greenhouse. Food Sci Technol Res 6:299-305. doi:10.3136/fstr.6.299

Verlent I, Smout C, Duvetter TMEH, Hendrickx ME, Van Loey A (2005) Effect of temperature and pressure on the activity of purified tomato polygalacturonase in the presence of pectins with different patterns of methyl esterification. Innovative Food Sci Emerg Technol 6:293-303. doi:10.1016/j.ifset.2005.02.003

Vilvert JC, De Freitas ST, Ferreira MAR, De Lima Leite RH, Dos Santos FKG, Costa CDSR, Aroucha EMM (2022) Chitosan and graphene oxide-based biodegradable bags: An eco-friendly and effective packaging alternative to maintain post-harvest quality of 'Palmer' mango. LWT 154:112741. doi:10.1016/j.lwt.2021.112741

Wang P, Yu A, Ji X, Mu Q, Haider MS, Wei R, Leng X, Fang J (2022) Transcriptome and metabolite integrated analysis reveals that exogenous ethylene controls berry ripening processes in grapevine. Food Res Int 155:111084. doi:10.1016/j.foodres.2022.111084

Wanitchang P, Terdwongworakul A, Wanitchang J, Nakawajana N (2011) Non-destructive maturity classification of mango based on physical, mechanical and optical properties. J Food Eng 105:477-484. doi:10.1016/j.jfoodeng.2011.03.006

Wei S, Mei J, Xie J (2021) Effects of edible coating and modified atmosphere technology on the physiology and quality of mangoes after low-temperature transportation at 13 C in vibration mitigation packaging. Plants 10:2432. doi:10.3390/plants10112432

Wongmetha O, Ke LS, Liang YS (2012) Sucrose metabolism and physiological changes during mango cv. Irwin growth and development. Hortic Environ Biotechnol 53:373-377. doi:10.1007/s13580-012-0078-3

Wongmetha O, Ke LS, Liang YS (2015) The changes in physical, bio-chemical, physiological characteristics and enzyme activities of mango cv. Jinhwang during fruit growth and development. NJAS Wageningen J Life Sci 72:7-12. doi:10.1016/j.njas.2014.10.001

Zahedi SM, Hosseini MS, Karimi M, Ebrahimzadeh A (2019). Effects of post-harvest polyamine application and edible coating on maintaining quality of mango (*Mangifera indica* L.) cv. Langra during cold storage. Food Sci Nutr 7:433-441. doi:10.1002/fsn3.802