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Spatial variance of physicochemical properties within mangos and the effect of initial ripeness stage on the quality of fresh-cut mangos

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BACKGROUND: This study aimed to assess the spatial variation in physicochemical properties within individual mangos, as well as to investigate the influence of initial ripeness level on physicochemical characteristics of fresh-cut mangos. Individual mangos were evaluated at 12 specific flesh positions in the inner and outer sides. Mango cubes of 1.5 cm prepared from three firmness stages were monitored for changes during 9 days of storage at 5 °C.

RESULTS: Mango fruit varied significantly in firmness and color based on spatial position, with the ripening direction from the inner flesh outward and from the stem end to blossom end. Limitations to fresh-cut mango quality were 'desiccation' (dried cut surface) and 'edge or tissue damage' (cut edge damage or brown and bruise-like appearance). Firmer texture and paler yellow of inner flesh were found in less mature mango fruit ($P < 0.001$). The optimal ripeness stage for fresh-cut mango products was 45 N, based on ease of handling, fresh appearance at the time of purchase and intermediate physicochemical properties (firmness, color and SSC/TA ratio).

CONCLUSION: Spatial variance and initial ripeness stage affect fresh-cut mango quality. Therefore, they must be considered by fresh-cut mango processors in order to attain optimal product quality.

Keywords: *Mangifera indica* L* mango; physicochemical properties; spatial variance; initial ripeness stage

INTRODUCTION

Mangos (*Mangifera indica* L.) are one of the most popular and economically significant of the tropical fruit crops and are widely distributed around the world. In 2013, mango ranked fifth after banana, apple, grape, and orange in terms of total production among the world's major fruit crops, with more than 43 million tons produced worldwide and 1.3 million tons exported, showing significant growth over previous years.[1] It is expected that the volume of fresh mangos in the world market will increase in coming years because of their attractive appearance, unique flavor (taste and aroma), and rich nutritional content. In general, mangos are harvested mature-green and then shipped to distant markets to minimize over-ripening, bruising and losses in quality during postharvest handling and transportation.[2]

The physicochemical properties of fresh fruits are important criteria for determining their quality. The main physicochemical characteristics related to the ripening quality of mangos are firmness, flesh and peel color, total soluble solids content (SSC), titratable acidity (TA) and aromatic volatiles.[2–5] Depending on the origin and cultivation practices, fruit quality and composition may vary greatly among fruits from the same lot.[6] Uneven ripening of mangos with the same initial peel colors packed in the same carton is a common problem in the mango industry. Besides the variability within the mango lot as a whole, previous studies suggest that individual mango tissues develop differently; also, mangos ripen from the inside outward, resulting in a softer inner mesocarp (flesh) than outer mesocarp at each stage of ripening.[5,7]

As a result, appropriate quality measurements are necessary to develop practical procedures for measuring and processing fresh-cut mangos. Fresh-cut mango processors utilize the entire mango fruit, and it is important to understand the range in quality parameters present in individual fruit at the time of processing. Although some previous studies refer to the quality changes in mango fruit during ripening and storage,[8–10] information regarding the effect of spatial position within whole mangos on quality measurements is lacking. From our previous studies, although 'Tommy Atkins' mangos with an initial whole fruit firmness of 25 N were best received by consumer, they are difficult to handle and store, with shorter shelf-life and lower yields in fresh-cut mango processing.[11] In this study, we are interested in the higher initial whole fruit firmness range of 35, 45 and 55 N specifically for fresh-cut processing.

The objectives of this study were (i) to measure the spatial variation in physicochemical characteristics within individual mangos and (ii) to investigate the influence of initial ripeness level on physicochemical characteristics of fresh-cut mango cubes, including the sensory evaluation scores, CIE $L^*a^*b^*$ color, firmness, SSC and TA.

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MATERIALS AND METHODS

Plant material

Mature green 'Tommy Atkins' mangos were purchased from a commercial wholesale store in Woodland, California. The mangos were imported from Mexico and Peru and had been subjected to hot-water quarantine protocols. On the day of mango arrival to the store, the fruit were purchased and transported to the Postharvest Pilot Plant at the University of California, Davis, in an air-conditioned vehicle. On the same day they were acquired, the mangos were visually sorted to eliminate damaged and defective fruit and were immersed in antimicrobial solutions containing 1.34 mmol L^{-1} sodium hypochlorite (NaOCl) at pH 7 for 3–5 min.

Study of spatial variation within mangos study

On the same day that mangos were acquired from a store, whole fruit firmness was non-destructively measured using a durometer (model Digital DD-3, Rex Gauge Company Inc., Buffalo Grove, IL, USA) on 30 'Tommy Atkins' mangos (nine count, mean fruit weight of 448 g). From the initial 30, 11 mangos with no significant difference in firmness ($P < 0.05$) (SAS version 9.0, Cary, NC, USA) and a mean initial firmness of 62.7 N were selected for this study. Each of the 11 mangos was sliced from stem to blossom end into two slabs on either side of the seed, and a 5 cm diameter section of the peel was removed from either side of the slab. The side of each slab originally close to the seed was designated 'inner', while the side of the slab closest to the mango cheek was designated 'outer'.

All analyses were analyzed at room temperature (20 °C). Flesh color and firmness were evaluated in six different positions on each of the two slabs (12 positions per mango, with 11 mangos totaling 132 positions): two positions on the outer flesh (near the cheek) and four positions on the inner flesh (near the seed). The different positions were along the 'stem scar to blossom end' axis or along the 'side-to-side' axis (Fig. 1). Subsequent to color and firmness measurements, each of the two slabs of the 11 mangos was sliced from stem end to blossom end into three sections (66 sections in total) – one center section and two side sections – for soluble solids content (SSC) and titratable acidity (TA) determinations.

Initial mango firmness levels study

Ninety 'Tommy Atkins' (nine count, mean fruit weight of 452 g) mangos, obtained as described above, were divided into three groups: the less mature fruit, which had firmness levels of 100–115 N; intermediately mature fruit, which had a firmness level of 80–99 N; and the most mature fruit, which had firmness levels of 60–79 N. All groups were then ripened at 20 °C with >90% relative humidity to prevent dehydration. Five fruit from each group were randomly selected every 1–2 days for a destructive firmness measurement using a penetrometer (described under 'Firmness' section below) until the fruit reached as close as possible to the mean of 55, 45 and 35 N, respectively. Mangos from each replicate of each firmness stage were evaluated when they reached the proper firmness level, but not necessarily on the same day. Five mangos were used for each firmness level for sensory evaluation and instrumental quality evaluations, and the study was replicated three times per firmness level (5 mangos × 3 replicates × 3 firmness levels = 45 mangos in total).

The entire cutting and packing process was conducted in a pre-sanitized 10 °C room. All cutting equipments, including knives, cutting boards and stainless steel strainers, were immersed in a 2.68 mmol L^{-1} NaOCl solution overnight at 10 °C prior to use. The 45 selected mangos were completely peeled with non-serrated knives and sliced from stem end to blossom end into two slabs on either side of the seed, as described above. The slabs were then cut into 1.5 × 1.5 × 1.5 cm cubes. Mango cubes from the same replicate for each firmness level were pooled together and were then dipped into antimicrobial solutions containing 1.34 mmol L^{-1} NaOCl (pH 7) at 10 °C for 2 min, drained and blotted dry with cheesecloth. In order to identify the specific side of each mango cube for instrumental quality measurements, an impression of approximately 1 mm deep was made using a 2 mm diameter cork borer, in the upper right corner of the side, when the outer side surface (near the cheek) was upright, prior to dipping into antimicrobial solution. The marks allowed identification of the cubes' outer side surface and did not cause color or firmness changes according to a preliminary study. The cubes from each evaluation day of each replicate were then transferred to the same polystyrene containers with lids and stored at 5 °C. On each storage day (days 1, 3, 5, 7 and 9), four mango cubes from each replicate were provided to each of six trained panelists for evaluation of sensory evaluation (24 cubes total per day; 120 cubes for all 5 days). An additional four cubes from each replicate were evaluated for instrumental quality (20 cubes for all 5 days).

Sensory quality evaluation

The six panelists were trained in a 1 h session to evaluate various mango cube samples for sensory evaluation using a subjective 9-point quality rating scale developed by Beaulieu and Lea.[12] This scale was based on 'overall color' (loss of yellow/orange color or pale), 'edge or tissue damage' (cut edge damage or brown and bruise-like appearance), 'decay', (obvious moldy or slimy surfaces), 'aroma'(strong off-odor or fermented aroma) and 'desiccation' (dried cut surfaces), where 9 = excellent, 7 = very good, 5 = good (limit of marketability), 3 = fair (limit of usability) and 1 = poor (unusable).[12] After the training session, the panelists practiced evaluating different mango samples using the 9-point rating scale. The overall quality score was calculated as the average of all subjective quality scores.

For the initial mango firmness level study, the three replicates of fresh-cut mango cubes from each firmness level (55, 45 and 35 N) were evaluated for quality evaluation on days 1, 3, 5, 7 and 9 of storage at 5 °C. Four mango cubes from each replicate were placed in a 59 mL polystyrene plastic cup with a lid (Solo Cup Company, Highland Park, IL, USA). A randomized block design was used for sample presentation sequences and samples were labeled with a random three-digit number before being presented to each panelist. The panelists evaluated the mango cubes in individual sensory booths at room temperature (20 °C).

Color evaluation

A Minolta Colorimeter (model CR-300, Minolta, Ramsey, NY, USA) calibrated with a standard white plate was used to measure color on the inner and outer flesh of each mango slab or to measure color on the inner and outer surfaces of each mango cube. Color was measured in the CIE $L^*a^*b^*$ color space mode and was expressed as lightness (L^*, (dark) 0–100 (bright)), green ($-a^*$) to red ($+a^*$), blue ($-b^*$) to yellow ($+b^*$) and a^*/b^* value, which indicated the intensity of orange coloration.[7] For the mango spatial variation study, the colors of the inner and outer flesh tissues of 11 mangos were evaluated (11 mangos × 2 slabs per mango × 6 measurements per slab = 132 measurements in total). For the initial mango firmness level study, the colors of four mango cubes from each replicate were measured on the inner (near the

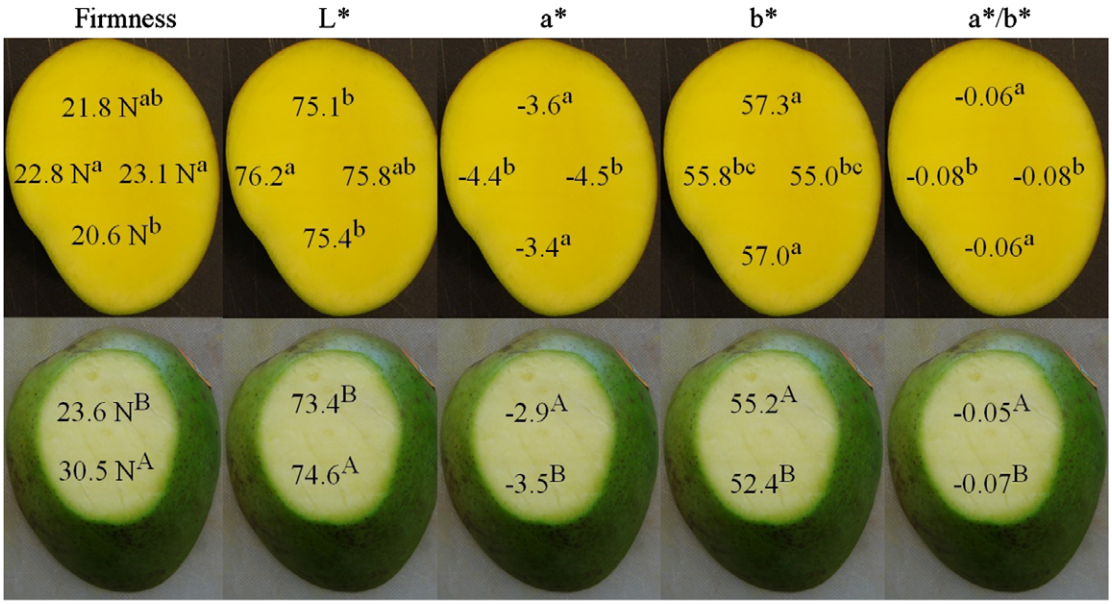

Figure 1. Average inner (upper row) and outer (lower row) flesh firmness and color values (CIE *L**, *a**, *b** and *a**/*b**) of whole Tommy Atkins mangos. Photos and measurements were taken on the day of mango purchase. Each value represents the mean of 11 fruits and two measurements per fruit.

seed) and outer side (near the cheek) on days 1, 3, 5, 7 and 9 of storage at 5 °C (3 firmness levels × 3 replicates per level × 4 cubes per replicate × 2 measurements per cube × 5 evaluation days = 360 measurements in total).

Firmness

For non-destructive and destructive firmness measurements of whole mangos, an individual fruit was supported by an 8.5 cm diameter aluminum cradle, manufactured at the University of California, Davis. For non-destructive measurements, the firmness of whole mangos was measured using a durometer (model Digital DD-3, Rex Gauge Company Inc.), equipped with a type 'E' tip (hemispherical in shape with 2.5 mm tip radius, 8.5 N spring force at full displacement, ASTM D2240) and fitted to an operating stand (model OS- 2H, Rex Gauge Company Inc.). The operating stand featured a load weight and a dampener, which lowered the durometer at the same rate for each measurement, increasing repeatability and eliminating operator error when measuring viscoelastic materials like mango. The firmness measurements were performed by dropping the type 'E' tip onto the mango fruit surface from an initial height (between the probe and fruit surface) of approximately 5 cm. Fruit deformation by the probe was less than 2.5 mm and typically did not cause noticeable damage to the peel or flesh.

For destructive firmness measurements, penetrometer firmness of whole or fresh-cut mangos was conducted using a texture analyzer (model TA.XT plus, Texture Technologies Corp., Scarsdale, NY, USA) equipped with a 5 kg load cell using a test speed of 5 mm s^{-1}. The firmness was measured as the maximum force required to penetrate 5 mm into the cut mango surface with an 8 mm diameter (for whole mango) or a 3 mm diameter (for mango cubes) flat-tipped cylindrical probe. For the mango spatial variation study, the firmness of both the inner and outer flesh of 11 mangos was measured after the mango was cut into two slabs and a 5 cm diameter section of skin was removed from two opposite sides of each slab. For the initial mango firmness level study, 45 whole mangos were initially selected according to firmness (3 firmness levels × 3 replicates per level × 5 mangos per replicate) by measuring the firmness of their outer flesh after a 5 cm diameter section of skin was removed from two opposite sides of each mango. The firmness of four mango cubes from each replicate was measured on the inner side (near the seed) and the outer side (near the cheek) on days 1, 3, 5, 7 and 9 of storage at 5 °C.

Soluble solids content (SSC), titratable acidity (TA) and SSC/TA ratio

For the mango spatial variation study, each of two slabs from the 11 whole mangos was sliced from stem end to blossom end into three sections (66 sections in total) for SSC and TA determinations. For the initial mango firmness level study, four cubes from each treatment replicate were used. Samples were juiced through two layers of cheesecloth with a hand juicer. A few drops of juice were used to measure SSC by refractometer (Reichert AR6 Series, Depew, NY, USA). 4 g (for whole mangos) or 2 g (for mango cubes) of juice was diluted in 20 mL deionized water for determination of TA (citric acid equivalents) using an automatic titrator (Tim850 titration manager connected to an SAC80 sample changer; Radiometer TitraLab, Lyon, France) on days 1, 3, 5, 7 and 9 of storage at 5 °C.

Statistical analysis

The firmness, CIE *L***a***b**, *a**/*b** value, SSC, TA and SSC/TA ratio of whole mango and fresh-cut cubes were analyzed using analysis of variance. Multiple means comparisons were performed using Fisher's least significant difference (LSD) at $P < 0.05$ to compare the physicochemical characteristics from different positions within mango and to compare the physicochemical characteristics of fresh-cut mango cubes from different initial firmness levels (SAS version 9.0, Cary, NC, USA).

RESULTS

Spatial variation of mango physicochemical characteristics

The penetrometer firmness and color of the inner and outer flesh tissues are presented overlaid on photos of the mango slabs in Fig. 1 as firmness, *L** (lightness), *a** (redness), *b**(yellowness) and

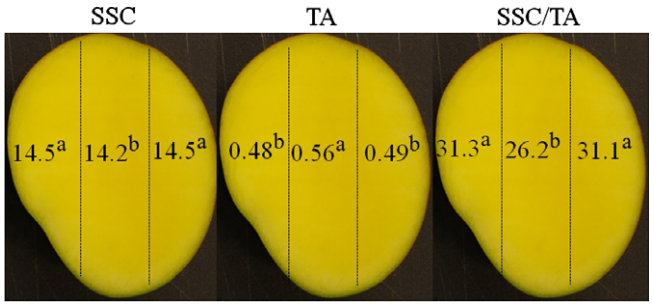

Figure 2. Average soluble solids content (SSC), total acidity (TA) and SSC/TA ratio of 'Tommy Atkins' mangos. Photos and measurements were taken on the day of mango purchase. Each value represents the mean of 11 fruit, with two measurements per fruit.

*a**/*b** (orange) values. The average outer flesh firmness of 'Tommy Atkins' mangos was 27.05 N, whereas the inner flesh firmness was significantly lower, with an average of 22.08 N ($P < 0.05$). The two positions measured from the side locations on the inner fruit slab showed no significant difference in firmness but were firmer than the flesh along the stem to blossom axis. However, there was a significant difference ($P < 0.05$) in firmness between the outer flesh positions, with the stem end (23.6 N) being significantly softer than the blossom end (30.5 N), by 6.9 N.

In general, 'Tommy Atkins' mangos had pale-yellow outer flesh and a brighter, deeper yellow-orange inner flesh color. There was a significant difference in flesh color ($P < 0.05$) between the outer flesh positions (Fig. 1, bottom row) and the inner flesh positions (Fig. 1, top row). In addition, the inner tissue along the stem to blossom axis was darker (lower *L** value), redder (higher *a** value), yellower (higher *b** value) and more orange (higher *a**/*b** value) than the tissue located along the side-to-side axis. The stem end of the outer flesh was darker, redder (or less green), yellower and deeper orange than the blossom end of the outer flesh.

In this study, the middle section of the mango flesh along the stem to blossom axis (Fig. 2) had lower SSC and SSC/TA ratio, and higher TA compared to mango flesh from the sides of the mango slab.

Fresh-cut mangos from different initial mango firmness levels

Sensory evaluation scores for fresh-cut mangos, including 'overall color', 'edge or tissue damage', 'decay', 'aroma', and 'desiccation', as well as cumulative averages of subjective sensory quality scores, are shown in Fig. 3, with lower quality scores indicating poorer sensory quality. All subjective scores and the cumulative subjective averages declined significantly ($P < 0.001$), for all initial firmness levels, throughout the 9 days of storage at 5 °C (Fig. 3 and Table 1); however, none of the attributes reached the limit of marketability (score < 5.0).[13] During storage, mango cubes tended to lose their bright-orange color (becoming paler yellow), to develop an off flavor, to become more translucent and to lose their wet gleam at the cut surface. Fruit that were initially firmer (55 and 45 N) had significantly paler yellow flesh and became more desiccated but had sharper cut surfaces, whereas mango cubes cut from softer whole fruits (35 N) showed more pronounced edge tissue damage ($P < 0.001$). There were no apparent differences in 'decay' or 'aroma' among stored 'Tommy Atkins' mango cubes cut from whole mangos at different initial firmness levels (Fig. 3C, D).

In our studies, the instrumental firmness and color evaluations were measured on both the inner side (near the seed) and outer side (near the cheek) of the mango cubes, and were presented separately due to their initial differences in the whole mango. There were slight declines in firmness in both the outer and inner sides of mango cubes from all initial firmness levels (55, 45 and 35 N) as storage time increased (Fig. 4A). Not surprisingly, the mango cubes from initially firmer fruits were significantly firmer than cubes from initially riper fruits ($P < 0.001$) (Table 1).

For fresh-cut mangos, a decrease in *L** value (lightness) can be used as an indicator of flesh browning,[8,14] and a higher *a**/*b** ratio indicates the development of a deeper orange color.[7] From our findings, the outer sides of the cubes had a greater flesh lightness (less browning) and less orange coloration (less *a**/*b** ratio) than the inner sides (near seed) (Fig. 4B, C and Table 1). Moreover, the color changes in the cubes measured on the outer sides were smaller than those measured on the inner sides. The mango cubes from the 55 N initial firmness group had more consistent outer flesh lightness, while the cubes from riper fruits (45 and 35 N) had significantly more browning and deeper orange development with storage time. However, the inner flesh lightness of all mango cubes increased throughout storage.

In this study, the measured SSC value was not found to be significantly different among the initial ripeness stages and days in storage (Table 1). In addition, the measured TA values did not correlate strongly with initial firmness levels of the mangos and days in storage. The SSC/TA values of the mango cubes varied significantly among firmness levels (Table 1). Mango cubes obtained from whole fruits that were initially firmer (i.e. 55 N) had lower SSC/TA. The SSC/TA values of the mango cubes increased slightly during the 9 days of storage at 5 °C.

DISCUSSION

Spatial variation of mango physicochemical characteristics

Consistent with a previous study,[7] the softer texture of the inner flesh as compared to the outer flesh indicates that 'Tommy Atkins' mangos initiate softening from the center (near the seed), spreading out to the outer part of the flesh (near the cheek), similar to 'Keitt', 'Haden', 'Harumanis', 'Kensington' and 'Mulgoa' mangos.[15] The difference in firmness between inner and outer flesh was previously found by other authors to become less pronounced as the fruit ripens[7] and also to depend on the mango cultivar, with larger differences observed in 'Harumanis' and 'Mulgoa' mangos than in 'Haden' and 'Kensington' mangos.[15] Mitcham and McDonald also reported that 'Keitt' mangos remained firm longer than 'Tommy Atkins' mangos during ripening.[7] Although a number of investigators have determined that mango ripening proceeds from the inside outward, our study is the first to establish that the direction of softening in the outer flesh was initiated at the stem end and progressed to the blossom end, as shown by the softer texture at the stem end.

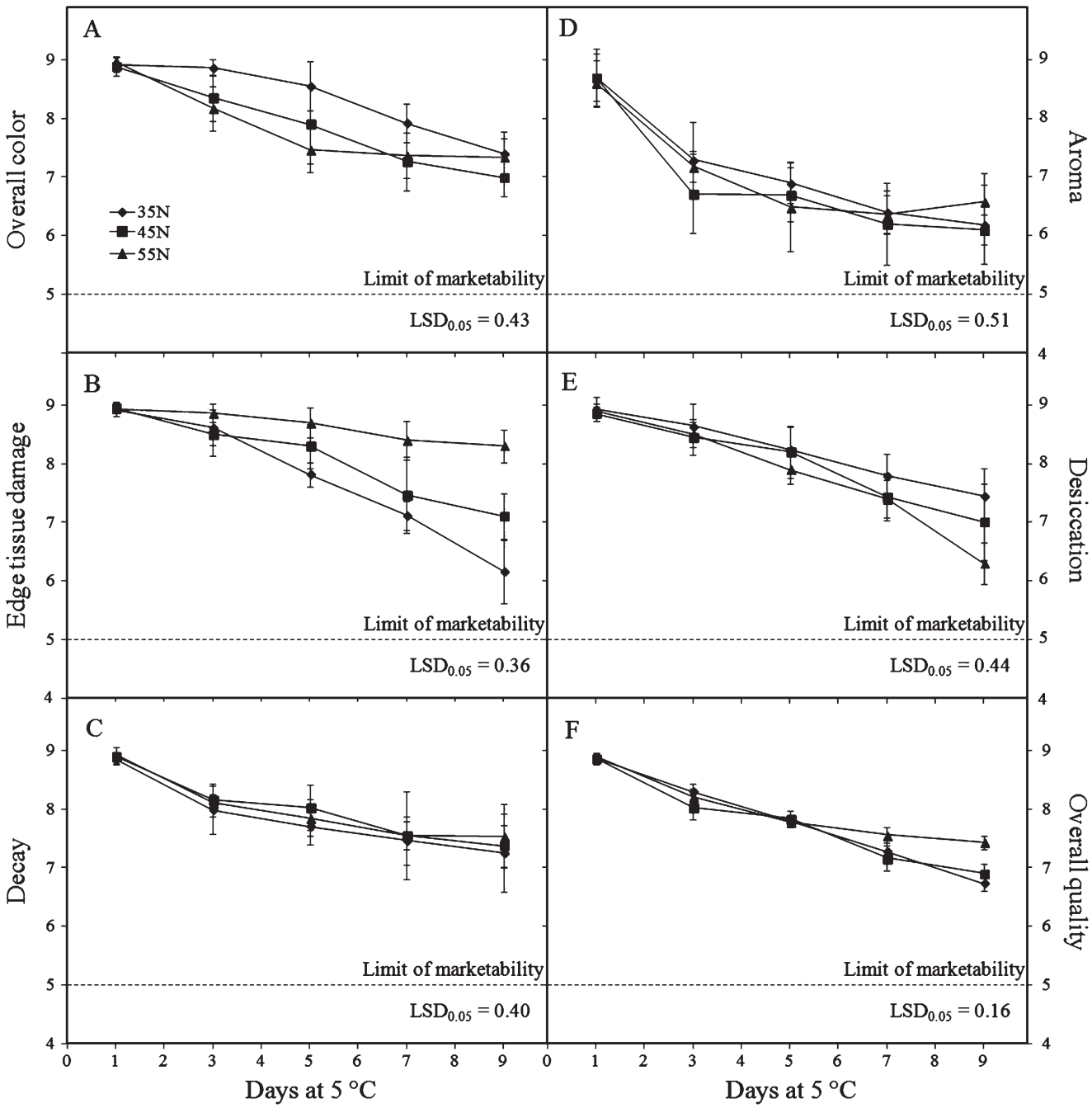

Figure 3. Sensory evaluation of overall color (A), edge tissue damage (B), decay (C), aroma (D), desiccation (E) and cumulative sensory quality score (F), for fresh-cut mango cubes from whole fruit with different initial flesh firmness of 55, 45 and 35 N (9, excellent; 5, limit of marketability, good; 1, poor, inedible).

In agreement with previous findings,[7,16] our results indicate that 'Tommy Atkins' mangos initiated color development from the inner flesh outward, with the center axis developing redder and more yellow-orange coloration as well as darker flesh than the sides of the mango slabs. The loss of green and the higher yellow-orange flesh color development may be associated with a progressive loss of chlorophyll and increase in carotenoid content and composition as the fruit ripens.[17,18] The decrease in lightness may be due to the development of enzymatic browning during ripening.[14]

For the SSC measurement, our findings are in disagreement with existing literature, which determined that higher SSC values were generally observed in the center part of the fruit, near the seed where ripening initiates.[2] These authors actually mixed mango flesh taken from the entire middle section, from the stem end to the blossom end; therefore they were not able to precisely determine the initial location. Our results indicate that the ripening rate is significantly different, with the stem end ripening faster than the blossom end. In this study we did not detect the difference in SSC, TA and SSC/TA ratio between inner and outer mango flesh. However, Chaplin *et al.* reported significantly higher SSC and lower TA for inner flesh than outer flesh, indicating the ripening of the fruit from the inner flesh outward.[15]

Table 1. Firmness, flesh color, SSC, TA, SSC/TA and overall quality score of fresh-cut 'Tommy Atkins' mangos cubes taken from whole fruit at different initial whole fruit firmness levels at the time of cutting, and stored at 5 °C

		Firmness (N)		Flesh color							
				Outer		Inner					
Days at 5 °C	Firmness stage	Outer	Inner	L^*	a^*/b^*	L^*	a^*/b^*	SSC (%)	TA (%)	SSC/TA	Overall quality score (1–9)
1	55 N	21.01	13.19	82.20	−0.15	73.35	0.00	12.70	0.94	13.60	8.9
	45 N	18.57	13.12	81.95	−0.11	74.26	0.03	13.40	0.78	17.32	8.9
	35 N	11.31	6.92	82.18	−0.07	73.30	0.04	13.10	0.96	13.78	8.9
3	55 N	23.24	12.06	82.40	−0.15	77.72	−0.02	13.25	0.99	13.46	8.1
	45 N	19.84	9.98	81.31	−0.08	73.27	0.05	14.10	0.93	15.10	8.0
	35 N	13.33	7.02	79.48	−0.08	73.18	0.05	14.40	1.02	14.36	8.4
5	55 N	22.03	12.58	82.57	−0.19	79.56	−0.02	13.45	1.20	11.71	7.7
	45 N	18.97	10.05	82.89	−0.09	76.79	0.03	14.55	0.98	14.86	7.8
	35 N	13.11	7.14	81.16	−0.08	72.98	0.06	14.05	1.20	12.19	7.9
7	55 N	20.50	12.91	83.23	−0.16	81.70	−0.04	13.40	1.20	11.38	7.3
	45 N	16.34	11.02	80.87	−0.08	78.66	0.03	15.05	0.92	16.39	7.2
	35 N	11.32	6.83	80.54	−0.07	73.88	0.04	14.65	1.10	13.28	7.5
9	55 N	17.68	13.59	81.91	−0.12	82.67	−0.06	13.90	0.95	14.94	7.1
	45 N	14.88	10.39	80.62	−0.09	80.33	0.00	14.90	0.86	17.30	6.9
	35 N	12.48	6.74	78.47	−0.06	77.14	0.02	14.95	0.91	16.54	7.1
Days at 5 °C (*D*)		n.s.	n.s.	n.s.	n.s.	(0.0001)	n.s.	n.s.	(0.0012)	n.s.	(0.0001)
Firmness stage (*F*)		(0.0001)	(0.0001)	(0.0022)	(0.0001)	(0.0001)	(0.0001)	n.s.	(0.0012)	(0.0191)	(0.0081)
$D \times F$		n.s.	n.s.	n.s.	n.s.	(0.0250)	n.s.	n.s.	n.s.	n.s.	(0.0001)

Each column, *P*-values are in parentheses; SSC, soluble solids content; TA, titratable acidity.

Fresh-cut mangos from different initial mango firmness levels

The most critical sensory quality factors, which resulted in a reduction in the quality of 'Tommy Atkins' mango cubes at all initial firmness levels, were 'edge or tissue damage' and 'desiccation', both of which resulted in poor appearance, followed by 'loss of aroma', 'discoloration' and 'decay' (Fig. 3). Our findings confirm a previous report from Beaulieu and Lea , who found that the quality of 'Palmer' and 'Keitt' mango cubes at both firm ripe and soft ripe stages (86–92 and 27–29 N initial flesh firmness, respectively, using a destructive penetrometer with a 11 mm probe) was limited by cut surface 'desiccation' and 'aroma' on day 7 of storage at 4 °C.[12] Dea also reported 'desiccation', 'aroma' and 'decay' as the primary quality limiting factors in fresh-cut 'Kent' mangos from an initial 35 N firmness stage (using a non-destructive compression test with 5 cm probe) and 'edge or tissue damage' as a limiting factor for riper fruits (30 and 25 N).[19]

However, in agreement with our previous study,[11] 'aroma' loss and the presence of 'decay' were not significantly different among stored 'Tommy Atkins' mango cubes cut from all firmness levels, which may be due to the inherently lower aroma intensity in whole 'Tommy Atkins' mangos as compared to 'Kent' mangos. Another factor may be due to the use of different texture methods, e.g. compression *versus* puncture/penetration, in measuring initial mango firmness. In general, when measuring the same whole mangos, we have determined that compression tests require as much as two times higher force values than puncture tests. In our study we used penetrometer firmness, as recommended by Padda *et al.*;[2] however, Dea utilized a non-destructive compression method and softer initial whole fruit.[19] Therefore, the trained panelists could not detect a difference in aroma among samples from various firmness levels of 'Tommy Atkins' mangos.

The mango cubes from all firmness levels were equally marketable according to the cumulative subjective averages, until day 7, at which time the 55 N mangos scored significantly higher in sensory quality until day 9 of storage (Fig. 3F). However, the mango cubes from the 55 N firmness level also had the highest 'desiccation', while the 35 N had the most 'edge or tissue damage'. Therefore, mango cubes from the 45 N firmness level may be the optimal initial firmness stage in terms of fresh appearance at the time of purchase, which is the primary criterion for consumers in terms of product quality.[20,21]

For the instrumental firmness and color evaluations, in agreement with our previous studies,[22] we found no significant decline in firmness in fresh-cut 'Tommy Atkins' mangos that were 35 N or higher in initial firmness level during storage. However, the decrease in firmness of stored mango cubes from riper initial fruit firmness (13–35 N) has been previously reported.[8,19,23] These authors observed rapid reduction in firmness of fresh-cut 'Haden', 'Kent', Keitt' and 'Ataufo' mangos due to greater susceptibility to wounding, resulting in more cell wall and cell membrane degradation, which subsequently caused more softening and greater turgor loss, compared to the initially firmer fruit used in our study. Moreover, none of these authors evaluated the difference in firmness of outer and inner sides of fresh-cut mangos. Our study found that in mango cubes from all firmness levels the firmness measured on the outer side of the cubes was higher than that on the inner side. The softer inner sides could be attributed to the ripening of mango from the inside outward.

Mango cubes from riper initial stages (i.e. 45 and 35 N) had less lightness and deeper orange development, potentially due to the development of enzymatic browning from ripening[14] and/or greater accumulation of carotenoids during fruit ripening.[18,24] The increased inner flesh lightness of all mango cubes throughout storage, in addition to a lessening in orange coloration (decrease in a^*/b^* ratio), led to a whiter appearance overall. This may stem from severe desiccation initiating from the first layer of damaged cells

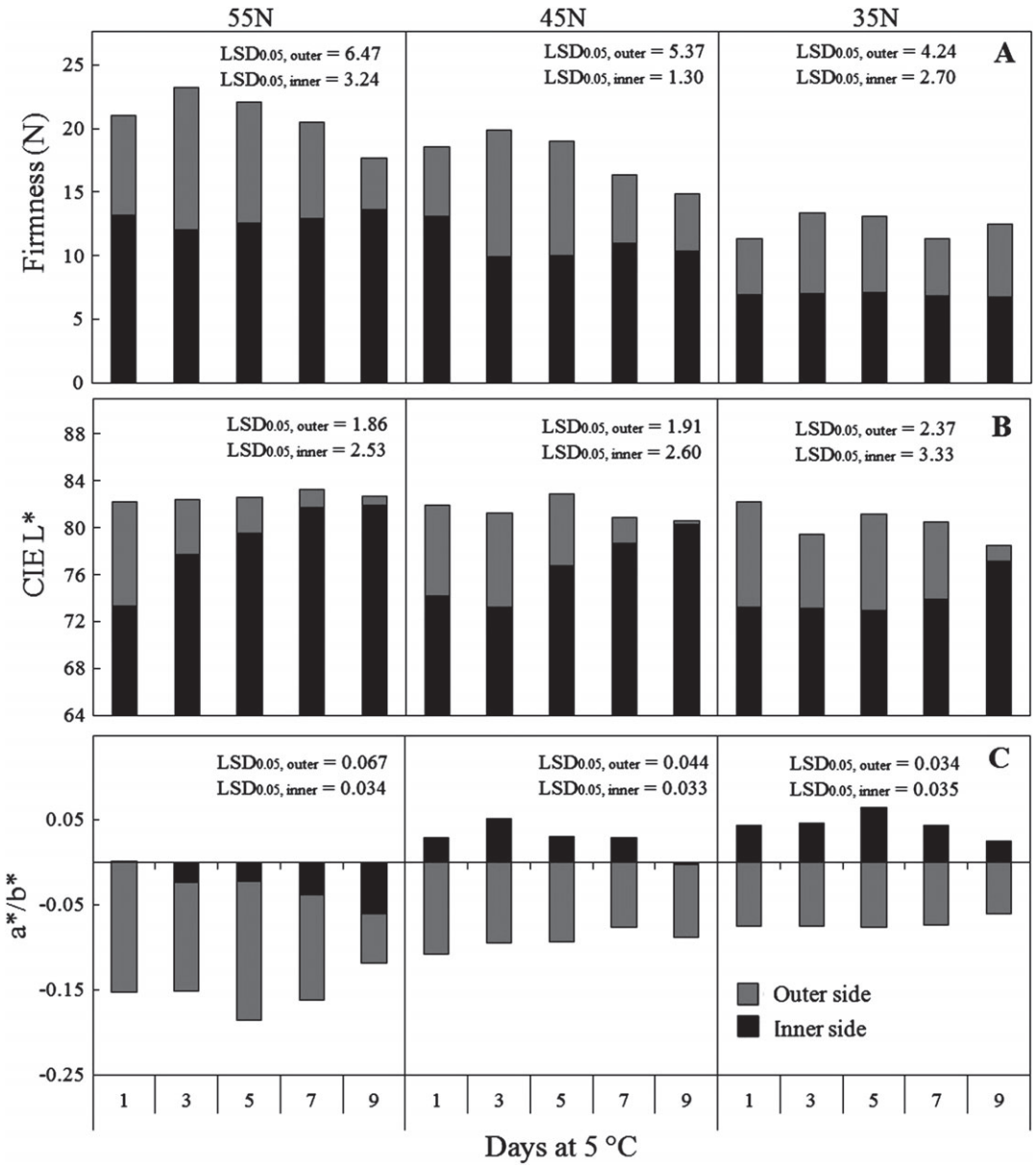

Figure 4. Firmness (A), L^* (B) and a^*/b^* (C) of outer side and inner side of fresh-cut mango cubes cut from mangos of different initial whole fruit outer flesh firmness, e.g. 55, 45 and 35 N. For each initial firmness stage, values with the same upper-case letter (outer-side firmness) or lower-case letter (inner-side firmness) were not significant difference ($P > 0.05$).

and progressing to additional internal cell layers.[25] Whitening was more prominent on mango cubes cut from initially firmer mangos.

In previous studies, SSC was suggested as an index for mango ripening.[2,26] In the current study, however, the measured SSC values were not suitable for initial ripeness stage differentiation or for monitoring mango quality changes during storage of fresh-cut 'Tommy Atkins' mangos, because there was no significant difference in the SSC values measured between firmness levels and days in storage.

In our previously published study, a consumer group of 140 evaluated mango cubes on the day of cutting and found that the 25 N mangos were the best received by consumers.[11] Our previous study also included a trained sensory panel evaluation of stored cubes on days 1, 5 and 9, but by day 9 in our current study we found that most cubes were beyond the limit of marketability. In the current study we expanded the sensory evaluation to days 1, 3, 5, 7 and 9 of storage at 5 °C and determined that mangos that were initially 45 N at the time of cutting maintained the highest fresh appearance at the time of purchase; therefore, these are recommended as the starting material for the fresh-cut mango industry.

CONCLUSIONS

This study determined the spatial variance of physicochemical properties within individual mangos, with a goal of developing methods for measuring and preparing mango samples for fresh-cut products. 'Tommy Atkins' mangos were found to ripen from the inside (near the seed) to the outside (near the cheek) and from the stem end and to blossom end. Mangos were found to vary

significantly in firmness and color based on the spatial position within the mango, and these factors must be considered when the mangos are used for fresh-cut products.

Overall, our study suggests that mango cubes from mangos with greater initial whole fruit flesh firmness had a firmer texture, a deeper orange flesh and a slightly lower SSC/TA value than mangos cubes prepared from initially softer fruits. The most critical factors, resulting in a reduction in mango cube quality, at all initial firmness levels, were 'edge or tissue damage' and 'desiccation'. Mango cubes from the 45 N initial firmness level are recommended as the optimal initial firmness stage for fresh-cut, on the basis of fresh appearance at the time of purchase and intermediate firmness, color development and SSC/TA ratio.

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