Postharvest Biology and Technology 189 (2022) 111917

Contents lists available at ScienceDirect

Postharvest Biology and Technology

journal homepage: www.elsevier.com/locate/postharvbio

Mango dry matter content at harvest to achieve high consumer quality of different cultivars in different growing seasons

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ARTICLE INFO

Keywords:
Mangifera indica L.
Market
Sensory analysis
Soluble solids content
Postharvest

ABSTRACT

Dry matter content (DMC) at harvest has been shown to be highly correlated with soluble solids content (SSC), which determines consumer acceptance of ripe mango. However, studies are required to evaluate the stability of the relationship among DMC x SSC x consumer acceptance for different mango cultivars under different climatic/seasonal growing conditions. The hypothesis of our study was that the minimum mango DMC required to achieve high consumer quality and acceptance is highly affected by the cultivar and climatic/seasonal growing conditions. The objective of this study was to determine the fruit DMC at harvest required to achieve high consumer quality and acceptance for 'Palmer' and 'Tommy Atkins' mangoes produced during the summer and winter growing seasons in the São Francisco Valley, Brazil. The DMC of 'Palmer' and 'Tommy Atkins' mangoes linearly increased during the last month before harvest in fruit produced in both growing seasons. During the last month before harvest, the DMC accumulation rates were 4.4 and 5.7 g kg^{-1} per week in 'Palmer' and 8.1 and 8.5 g kg^{-1} per week in 'Tommy Atkins' mangoes produced in the summer and winter, respectively. At harvest, a portable Vis-NIR spectrometer was used to non-destructively determine the DMC of 'Palmer' and 'Tommy Atkins' mangoes that were then grouped into three different DMC categories for each cultivar and season, with ranges from 50 to 80 g kg^{-1}. The fruit were then kept at 12 °C with relative humidity of 90–95% to simulate the shipping conditions, until they reached the ready-to-eat ripeness stage, with flesh firmness ≤ 15 N. The fruit were then subjected to physicochemical and sensory analyses. Higher DMC at harvest results in higher soluble solids content in ripe mangoes. Minimum DMC values at harvest to guarantee that consumers will respond with at least "like moderately" (score of 7 out of 9) in sensory testing of mango fruit were found to be 137 g kg^{-1} and 145 g kg^{-1} for 'Palmer' and 144 g kg^{-1} and 153 g kg^{-1} for 'Tommy Atkins' for summer and winter harvests, respectively. The minimum mango DMC required to achieve high consumer quality and acceptance was weakly related to cultivar and climatic/seasonal growing conditions.

1. Introduction

Mango (*Mangifera indica* Linn.) is one of the most consumed fruits in the world and is mainly produced in tropical and semi-tropical regions (Brecht and Yahia, 2009; Saúco, 2015). In Brazil, most of the mango production is located in the São Francisco Valley in the Northeast, which produces mainly 'Tommy Atkins' and 'Palmer' mangoes (Brazilian Horti & Fruti Yearbook, 2021). The region is characterized by a semi-arid climate with high sunlight hours, temperatures and low precipitation during the year (Bezerra Sá et al., 2009). Under such conditions, proper crop management practices allow producing mangoes throughout the year to supply the national and international markets (Simões et al., 2020).

Mango fruit has a tropical flavor determined by genotype, environmental conditions, and fruit quality at harvest (Liguori et al., 2020). Therefore, accurate harvest indices must be established to determine when to harvest each genotype in each environmental condition in order to guarantee delivery of high quality fruit to consumers. Currently,

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https://doi.org/10.1016/j.postharvbio.2022.111917
Received 2 January 2022; Received in revised form 20 March 2022; Accepted 21 March 2022
Available online 28 March 2022
0925-5214/

mango harvest in many countries is still based on fruit visual appearance and flesh color, which results in high variability of ready-to-eat fruit quality (Léchaudel and Joas, 2007; Assis and Lima, 2008). Indeed, previous studies have shown that mango external and internal visual appearance, which is mainly determined by chlorophyl and carotenoid contents, are highly affected by the environmental conditions (Léchaudel and Joas, 2007; Golob et al., 2012; Motomura et al., 2013; Yusuf et al., 2018). For instance, 'Keitt' mangoes produced in the hotter climate of Bahia, Brazil have more than twice the carotenoid content as 'Keitt' mangoes produced in the colder climate of São Paulo, Brazil (Mercadante and Rodriguez-Amaya, 1998). These studies suggest that visual color changes are highly dependent on the environmental conditions that can be affected by seasonal, location, and orchard conditions, as well as by fruit position on the plant, resulting in different chlorophyl and carotenoid synthesis/breakdown and estimation of fruit maturity index. Recently, studies have shown that mango dry matter content (DMC) at harvest has a strong correlation with ripened fruit quality (Subedi and Walsh, 2011; Jha et al., 2012; Nordey et al., 2016; Anderson et al., 2020; Hor et al., 2020). In that case, using DMC together with other quality traits will help in determining the optimal harvest time required to satisfy consumer quality demands.

Mango DMC is mostly composed of structural and storage carbohydrates that accumulate in the fruit during growth and development on the plant, with accumulation of starch predominating during the period closest to fruit physiological maturity (Maldonado-Celis et al., 2019). After harvest, during postharvest ripening, carbohydrates are broken down into soluble sugars, contributing to mango sweetness and flavor (Nordey et al., 2016; Maldonado-Celis et al., 2019; Liguori et al., 2020; Hor et al., 2020). For that reason, mango DMC at harvest is considered a more reliable and objective harvest index than visual appearance alone to determine fruit maturity and predict consumer quality and acceptance of the ripe fruit (Jha et al., 2012; Anderson et al., 2017; Sung et al., 2019; Anderson et al., 2020; Hor et al., 2020). The DMC required at harvest to guarantee positive consumer acceptance have been determined for 'Kensington Pride' (150 g kg^{-1}), 'R2E2' (130 g kg^{-1}), 'Calypso' (150 g kg^{-1}), and 'Honey Gold' (150 g kg^{-1}) mangoes in Australia (Australian Mango Industry Association, 2015), as well as for other mango cultivars in the consumer market (González-Moscoso, 2014). However, the minimum DMC must be determined at harvest for each genotype and growing condition to guarantee high fruit quality to consumers.

Although continuous carbohydrate uptake results in increasing DMC in mangoes during growth and development on the plant, fruit carbohydrate accumulation is known to vary from fruit-to-fruit due to factors that affect plant photosynthesis and fruit competition for phloem sap uptake (Grechi and Normand, 2019). Therefore, fruit at the same maturity stage at harvest can have different dry matter contents (DMCs) that may result in different eating quality. In that case, determining the minimum mango DMC that guarantees high consumer quality can help in establishing quality standards and values for different fruit classes.

Fruit carbohydrate uptake is known to be highly affected by environmental conditions such as sunlight, temperature, and water availability, which have been shown to affect fruit DMC at harvest and subsequently eating quality (Léchaudel and Joas, 2007). For example, low light intensity has been shown to reduce leaf photosynthesis and mango DMC (Léchaudel and Joas, 2007). Different rates or amounts of mango carbohydrate uptake under different environmental conditions can alter carbohydrate allocation in the cells, affecting synthesis of the sugars, acids, and volatiles that determine fruit flavor (Léchaudel and Joas, 2007). Therefore, considering that mango production in the São Francisco Valley in Brazil takes place during the whole year under different environmental conditions, the region provides an ideal opportunity to study the effect of the environment on dry matter accumulation in mango fruit and to determine the minimum DMC in different growing seasons that is required to guarantee consistent high fruit quality to consumers.

Therefore, dry matter content (DMC) at harvest has been shown to be highly correlated with soluble solids content (SSC) that determines consumer acceptance of ripe mango. However, studies are required to evaluate the stability of the relationship among DMC x SSC x consumer acceptance for different mango cultivars under different climatic/seasonal growing conditions. The hypothesis of our study is that the minimum mango DMC required to achieve high consumer quality and acceptance is highly affected by the cultivar and climatic/seasonal growing conditions.

The objective of this study was to determine the fruit DMC at harvest required to achieve high consumer quality and acceptance for 'Palmer' and 'Tommy Atkins' mangoes produced during the summer and winter growing seasons in the São Francisco Valley, Brazil.

2. Materials and methods

'Tommy Atkins' and 'Palmer' mangoes were produced during the summer and winter growing seasons in 2018/2019 in commercial orchards located in the São Francisco Valley, Northeast of Brazil (8° 45′ 31″ S, 38° 57′ 45″ W) and were harvested in April and October, respectively. The commercial orchards used in the study were subjected to the same management practices in both growing seasons. The climatological data were collected in the same region along the growing seasons with a weather station equipped with precipitation sensor (CS700-L, Hydrological Services Rain Gauge, Liverpool, Australia), air temperature and relative humidity sensors (HMP45C, Vaisala, Vaisala, Finland), and global radiation sensor (CNR1 Net radiometer - Kipp & Zonen B.V. Delft Netherlands).

A total of 300 fruit of each genotype were repeatedly analyzed non-destructively for DMC every week during the last month before harvest. The DMC was analyzed with a Vis-NIR spectrometer F-750 (Felix Instruments, United States), which was previously calibrated with 200 'Tommy Atkins' and 'Palmer' mangoes produced in the São Francisco Valley, Brazil. The DMC models were developed for each cultivar following the F-750 protocol, using the F-750 Model Builder Software (Felix Instruments, United States).

Mango harvest was accomplished according to the commercial recommendations, based on fruit shape and color (Assis and Lima, 2008). The harvests of each cultivar were conducted on the same farm on both harvest dates. Commercially harvested fruit of each cultivar were non-destructively classified into three DMC ranges, using the F-750 Vis-NIR spectrometer, with each DMC range composed of 120 fruit. Fruit produced during the summer were harvested in April, whereas fruit produced during the winter were harvested in October. In the April harvest, 'Palmer' mangoes were sorted into DMC ranges of 100–120 g kg^{-1}, 130–150 g kg^{-1}, and 160–180 g kg^{-1}, while 'Tommy Atkins' mangoes were sorted into the DMC ranges of 100–110 g kg^{-1}, 120–130 g kg^{-1}, and 140–150 g kg^{-1}. In the October harvest, 'Palmer' mangoes were sorted into the DMC ranges of 120–130 g kg^{-1}, 140–150 g kg^{-1}, and 160–170 g kg^{-1}, while 'Tommy Atkins' mangoes were sorted into the DMC ranges of 110–120 g kg^{-1}, 130–140 g kg^{-1}, and 150–160 g kg^{-1}. These ranges represent the variability of the DMC observed for each cultivar in each growing season. In that case, the three DMC ranges taken together represent the majority of the fruit population in the orchard.

All fruit were washed with tap water and dried at room temperature (25 °C ± 1 °C) in the Postharvest Laboratory at Embrapa, Petrolina, PE, Brazil. For each DMC range, a 20-fruit sample was used for physicochemical analyses at harvest, whereas the remaining 100-fruit samples of each DMC range were stored at 12 °C with relative humidity of 90–95% to simulate the shipping conditions. After reaching the ready-to-eat maturity (flesh firmness ≤ 15 N), the fruit were then subjected to physicochemical and sensory analysis, as described below.

2.1. Physicochemical quality

Mango physicochemical quality was characterized by fruit flesh firmness (FF), soluble solids content (SSC), titratable acidity (TA), SSC/TA ratio, and skin color (SC) and flesh color (FC). The FF was determined with a texture analyzer TA.XT/Plus (Extralab, São Paulo, Brazil), equipped with a 6 mm diameter probe. The results were expressed in Newtons (N), representing the force necessary for the probe to penetrate 10 mm into the fruit flesh without the skin. The SSC of a 1-mL sample of mango juice was determined with a digital refractometer Pal-1 (Atago, São Paulo, Brazil). The results were expressed as the percentage of SSC in the juice. The juice TA was determined by titrating 1 g of mango juice, diluted in 50 mL of distilled water, with a solution of 0.1 mol L^{-1} of NaOH, until pH 8.1 was reached. Titration was accomplished with an automatic titrator 848 Tritino Plus (Metrohm, São Paulo, Brazil) and the results were expressed as percentage of citric acid. The SSC/TA ratio was obtained by dividing the SSC value by its respective TA value. The SC and FC were determined with a CR-400 colorimeter (Konica Minolta, USA). The results were expressed in the coordinates L* (Lightness), C (Chroma) and °h (hue angle), according to the CIE L*a*b* system.

2.2. Consumer test

The sensory analysis was previously approved by the Ethics Committee under CAAE number of 06323119.7.0000.5196. After the physicochemical quality analyses, fruit from each DMC range were peeled and the flesh uniformly cut into 1 cm^3 cubes. Later, a total of 35 g of flesh cubes from each DMC range were placed into 100-mL white cups that were coded with a three-digit number. For each consumer, a group of three cups, representing the three DMC ranges of each cultivar and growing season, was presented in a monadic order. The effects of the presentation order and first-order carry-over were controlled using the crossover design (Wakeling and MacFie, 1995). The samples were submitted for acceptance testing with 205 consumers (100 women and 105 men), aged between 18 and 66 years old for fruit harvested in April, and with 140 consumers (72 women and 68 men), aged between 18 and 67 years old for fruit harvested in October. The volunteers were recruited among mango consumers at least once a week.

The sensory analysis was accomplished in individual booths, under incandescent white illumination and at a temperature of 22 °C. First, all the consumers evaluated the acceptability of the appearance, flavor, texture, and overall satisfaction with the mango samples using a 9-point hedonic scale (1 = disliked extremely, 5 = neither like not dislike, 7 = liked moderately, 9 = liked extremely). Later, a non-structured 9-cm scale was also applied, which was anchored at the extremes with the terms “low intensity” and “high intensity”, to evaluate the intensity of the attributes sweetness, acidity, juiciness and fibrousness (Ferreira et al., 2000; Torrezan et al., 2004; Martim et al., 2006).

2.3. Statistical analysis

The DMC accumulation during the last month before harvest was presented as mean value ± standard deviation (SD). The study followed a completely randomized design with three treatments represented by the three DMC ranges of each cultivar in each growing season. Each fruit was considered one replication. Physicochemical analyses were conducted on samples composed of 20 fruit per treatment at harvest and 100 fruit per treatment after storage. Consumer analyses were conducted using 100 fruit per treatment. The data from the physicochemical and consumer analyses were subjected to analysis of variance (ANOVA) using the SISVAR statistical program and the mean values were compared by Tukey’s test at 5%. The consumer’s overall satisfaction and DMC data of each cultivar in each growing season were used to obtain linear equations that were used to estimate the minimum DMC that the fruit should have at harvest to ensure high consumer acceptance, considering the overall satisfaction equal to 7 (“liked moderately”) in the 9-point hedonic scale.

3. Results

3.1. Fruit growing conditions and DMC accumulation

The durations of fruit growth and development from full bloom to harvest were 90 and 110 d for ‘Tommy Atkins’, and 130 and 150 d for ‘Palmer’ mangoes during the summer and winter growing seasons, respectively. The environmental data show higher precipitation during the summer, compared to the winter growing season (Fig. 1). The monthly average RH, air temperature and global radiation (GR) oscillated between 45% and 62%, 29–25 °C, and 26–18 MJ m^{-2} d^{-1} in both growing seasons (Fig. 1).

DMC of ’Palmer’ and ’Tommy Atkins’ mangoes increased linearly during the last month before harvest for fruit produced in both the summer and winter growing seasons (Figs. 2 and 3). No statistical differences were observed for DMC accumulation between growing seasons. During the last month before harvest, DMC accumulation rates were 4.4 and 5.7 g 1 kg^{-1} per week in ‘Palmer’ and 8.1 and 8.5 g kg^{-1} per week in ‘Tommy Atkins’ mangoes produced in the summer and winter, respectively (Figs. 2 and 3). In both growing seasons, each cultivar showed a high variability in DMC accumulation between fruit during the last month before harvest, resulting in high variability of fruit DMC at harvest (Figs. 2 and 3).

3.2. Fruit DMC and physicochemical quality

At harvest, ‘Palmer’ mangoes with higher DMC showed flesh color with higher L and °h, as well as lower C values in both growing seasons (Table 1). In April, the highest L value was observed in mangoes harvested with 160–180 g kg^{-1} DMC, the lowest C and the highest °h values were observed in mangoes harvested with 130–180 g kg^{-1} DMC, whereas SSC and TA were statistically equal among the different DMC ranges (Table 1). In October, the highest L and the lowest C values were observed in mangoes harvested with 160–170 g kg^{-1} DMC, the highest °h was observed in mangoes harvested with 140–170 g kg^{-1} DMC, whereas the highest SSC was observed in fruit harvested with 160–170 g kg^{-1} DMC and no statistical difference was observed for TA among different DMC ranges (Table 1).

After storage, ‘Palmer’ mangoes harvested with higher DMC had higher SSC (Table 1). In April, the highest L values were observed in mangoes harvested with 100–150 g kg^{-1} DMC, whereas the highest °h value was observed in fruit harvested with 130–150 g kg^{-1} DMC and no statistical differences were observed for C and TA values among

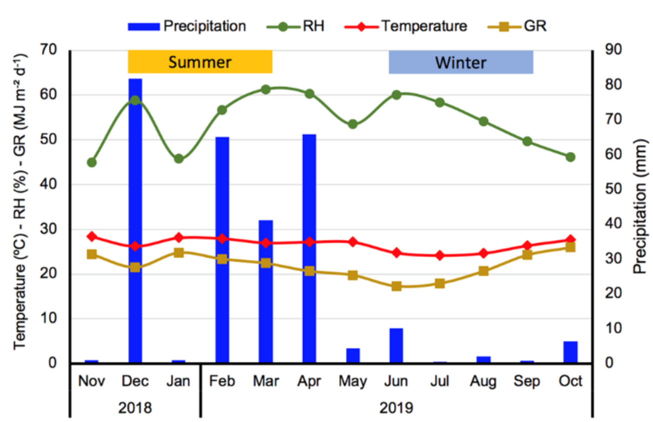

Fig. 1. Precipitation, relative humidity (RH), air temperature and global radiation (GR) during the summer and winter growing seasons of ‘Tommy Atkins’ and ‘Palmer’ mangoes in the São Francisco Valley. Mangoes produced during the summer and winter were harvested in April and October, respectively.

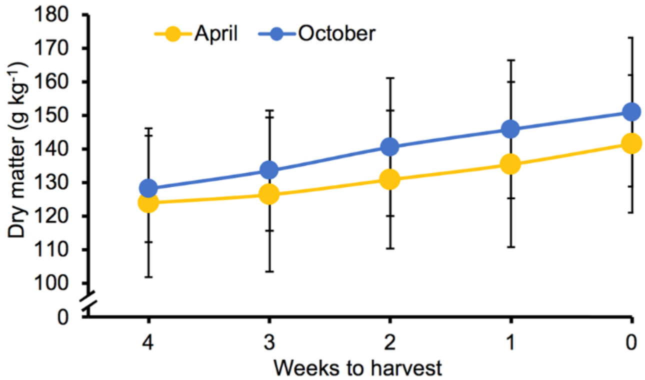

Fig. 2. Dry matter accumulation in 'Palmer' mangoes prior to harvest. Fruit were produced in the summer and winter and harvested in April and October, respectively. Harvest was accomplished at week 0. Data are means ± SD.

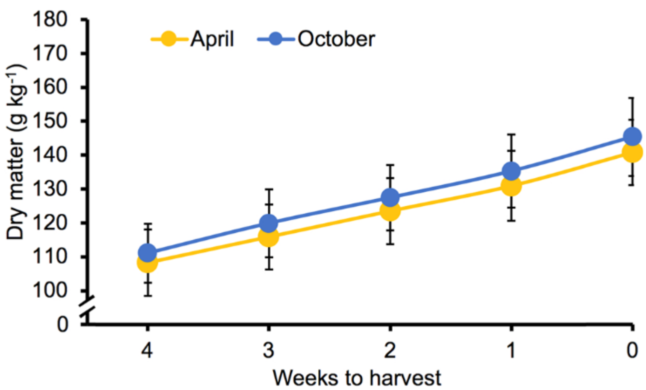

Fig. 3. Dry matter accumulation of 'Tommy Atkins' mangoes prior to harvest. Fruit were produced in the summer and winter and harvested in April and October, respectively. Harvest was accomplished at week 0. Data are means ± SD.

different DMC ranges (Table 1). In October, the highest L values were observed in mangoes harvested with 120–150 g kg^{-1} DMC, whereas the highest C and SSC values, and the lowest °h and TA values were observed in mangoes harvested with 140–170 g kg^{-1} DMC ranges (Table 1).

At harvest, 'Tommy Atkins' mangoes picked in April with 140–150 g kg^{-1} DMC showed higher flesh L and C values, whereas mangoes with 120–130 g kg^{-1} DMC showed higher °h values, compared to other DMC ranges (Table 2). 'Tommy Atkins' mangoes harvested in April with different DMC ranges had the same SSC and TA (Table 2). In October, 'Tommy Atkins' mangoes harvested with 150–160 g kg^{-1} DMC showed flesh color with the lowest L and the highest C values, as well as the highest SSC and the lowest TA (Table 2). Fruit harvested with 110–120 g kg^{-1} DMC had the highest flesh °h value (Table 2). After storage, 'Tommy Atkins' mangoes harvested with higher DMC had flesh color with lower L and °h values and higher C value, as well as higher SSC (Table 2). 'Tommy Atkins' mangoes harvested in October with different DMC ranges had the same TA after storage (Table 2). Considering the data obtained from both cultivars and growing seasons, higher mango DMC at harvest resulted in higher SSC once the fruit ripened to the ready-to-eat stage (Fig. 4).

3.3. Fruit DMC and consumer quality

According to the consumer analysis, 'Palmer' mangoes harvested in April with 130–180 g kg^{-1} DMC had the highest scores for overall satisfaction, flavor, appearance, and texture, as well as showed the highest sweetness intensity (Table 3). Mangoes harvested with 160–180 g kg^{-1} DMC also showed the highest juiciness and fibrousness intensities (Table 3). In April, 'Palmer' mangoes harvested with different DMCs showed similar acidity intensity, after reaching the ready-to-eat ripeness stage (Table 3). 'Palmer' mangoes harvested in October with 140–170 g kg^{-1} DMC had the highest scores for overall satisfaction, flavor, appearance, and texture, as well as showed the highest juiciness intensity (Table 3). Mangoes harvested with 160–170 g kg^{-1} DMC also showed the highest sweetness and the lowest acidity intensities (Table 3). In October, 'Palmer' mangoes harvested with different DMCs showed similar fibrousness intensity after reaching the ready-to-eat ripeness stage (Table 3).

'Tommy Atkins' mangoes harvested in April with 140–150 g kg^{-1} DMC had the highest scores for overall satisfaction, flavor, and appearance, as well as showed the highest sweetness, acidity, juiciness, and fibrousness intensities (Table 4). No statistical difference was observed for texture acceptance among fruit with different DMCs (Table 4). 'Tommy Atkins' mangoes harvested in October with 150–160 g kg^{-1} DMC had the highest scores for overall satisfaction, flavor, and texture, as well as showed the highest sweetness and juiciness intensities (Table 4). Mangoes harvested with 130–160 g kg^{-1} DMC also showed the highest acidity intensities (Table 4). In October, 'Tommy Atkins' mangoes harvested with different DMCs showed similar appearance acceptance and fibrousness intensity, after reaching the ready-to-eat ripeness stage (Table 4).

The results obtained show a positive linear relationship between mango DMC at harvest and consumer responses for fruit overall satisfaction. In that case, higher mango DMC at harvest results in higher overall satisfaction (Figs. 5 and 6). Considering the consumer overall satisfaction analysis to determine the minimum DMC that mangoes should have at harvest to guarantee the minimum consumer acceptance of 7 ("liked moderately"), our results show that to guarantee the minimum consumer acceptance 'Palmer' or 'Tommy Atkins' mangoes must have a minimum of 137 g kg^{-1} and 145 g kg^{-1} or 144 g kg^{-1} and 153 g kg^{-1} DMC at harvest when produced in the summer and winter, respectively (Figs. 5 and 6).

Table 1
Physicochemical analyses of 'Palmer' mangoes produced in the São Francisco Valley, harvested with different dry matter (DMC) ranges in April and October and stored at 12 °C until the fruit reached the ready-to-eat stage with flesh firmness ≤ 15 N.

Harvest	DMC (g kg^0)	At harvest					After storage at 12 °C				
		Flesh color			SSC (%)	TA (%)	Flesh color			SSC (%)	TA (%)
		L	C	°h			L	C	°h		
April	100–120	80.8 b[a]	41.6 a	104.0 b	6.2 a	1.0 a	73.8 a	63.5 a	88.1 b	9.8c	0.5 a
	130–150	81.9 b	33.4 b	107.7 a	5.9 a	1.1 a	74.7 a	64.2 a	91.0 a	12.3 b	0.5 a
	160–180	83.8 a	34.9 b	106.8 a	5.8 a	1.1 a	72.3 b	64.7 a	89.4 b	15.4 a	0.6 a
October	120–130	73.1 b	60.4 a	89.2 b	7.8 b	1.2 a	72.3 a	61.0 b	88.5 a	11.0 b	0.4 a
	140–150	75.3 b	60.2 a	90.2 a	9.1 b	1.1 a	71.7 ab	66.4 a	86.0 b	13.5 a	0.3 b
	160–170	77.1 a	56.8 b	91.9 a	11.2 a	1.0 a	69.6 b	66.1 a	85.3 b	15.0 a	0.3 b

[a] Means followed by the same letter in each harvest are statistically equal according to the Tukey's test (5%).

Table 2
Physicochemical analyses of 'Tommy Atkins' mangoes produced in the São Francisco Valley, harvested with different dry matter (DMC) ranges in April and October and stored at 12 °C until the fruit reached the ready-to-eat stage with flesh firmness ≤ 15 N.

Harvest	DMC (g kg^{-1})	At harvest					After storage at 12 °C				
		Flesh color			SSC (%)	TA (%)	Flesh color			SSC (%)	TA (%)
		L	C	°h			L	C	°h		
April	100–110	76.9 b[a]	51.5 b	99.9 b	5.5 a	1.2 a	67.5 b	57.2 b	86.1 b	11.0 b	0.9 b
	120–130	76.3 b	51.4 b	100.4 a	5.4 a	1.2 a	77.0 a	64.3 a	93.2 a	11.7 b	1.2 a
	140–150	77.2 a	54.1 a	99.8 b	5.2 a	1.5 a	76.2 a	62.3 a	90.6 a	12.3 a	1.1 a
October	110–120	75.7 a	55.0c	94.5 a	8.4c	1.2 a	76.3 a	59.4 b	91.5 a	9.7 b	0.4 a
	130–140	72.5 ab	61.9 b	89.7 b	10.1 b	1.0 a	73.7 b	64.6 ab	89.0 ab	11.7 ab	0.5 a
	150–160	70.7 b	64.2 a	87.4 b	12.7 a	0.6 b	67.2 b	66.0 a	85.0 b	13.9 a	0.4 a

[a] Means followed by the same letter in each harvest are statistically equal according to the Tukey's test (5%).

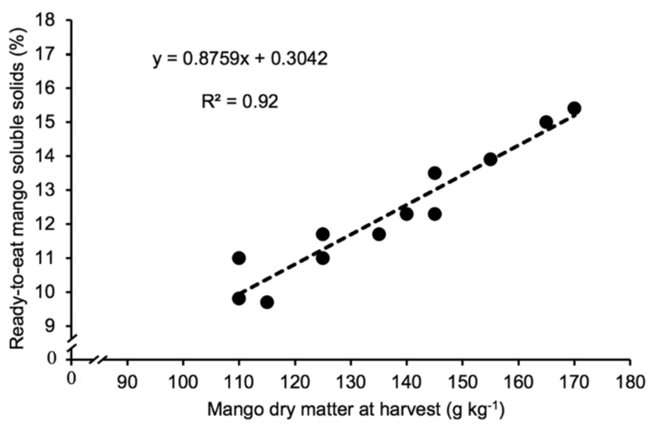

Fig. 4. Relationship between fruit dry matter content (DMC) at harvest and soluble solids content (SSC) in ripe, ready-to-eat 'Tommy Atkins' and 'Palmer' mangoes with flesh firmness equal to or lower than 15 N. Each point represents the average of 100 fruit harvested at each DMC range in April and October. Total = 1200 fruit (600 'Palmer' and 600 'Tommy Atkins' mangoes).

4. Discussion

Although previous studies have suggested that mango DMC at harvest is an important index to predict ready-to-eat fruit quality, all these studies have been conducted with fruit produced in the summer season and/or compared fruit from different growing locations at the final market (Subedi and Walsh, 2011; Jha et al., 2012; Nordey et al., 2016; Anderson et al., 2017; Maldonado-Celis et al., 2019; Sung et al., 2019; Hor et al., 2020; Liguori et al., 2020). In our study, different mango cultivars were produced in the same orchard management conditions during summer and winter growing seasons in the same location. These conditions allowed us to better understand the effects of the different growing seasons and genotypes on mango DMC accumulation until harvest, as well as to determine with high precision the minimum DMC required at harvest to ensure high fruit quality and consumer satisfaction.

4.1. Dry matter accumulation in mangos cultivated during the summer and winter environmental conditions

The results of this research showed that the average fruit DMCs at harvest were about the same for both mango cultivars and growing seasons. The lack of seasonal effect on average mango DMC accumulation could be explained by the fact that the most important environmental factors contributing to fruit DMC, such as GR, temperature, and RH were also similar in both growing seasons. Although precipitation was higher in the summer compared to the winter, mango orchards in the São Francisco Valley are irrigated, which possibly reduced the precipitation effect on fruit DMC accumulation between growing seasons. The similar average fruit DMCs observed at harvest in both mango genotypes was due to the combined effects of fruit DMC accumulation rate and time of fruit growth and development. In that case, 'Palmer' mango had lower DMC accumulation rates and longer periods of fruit growth and development, whereas 'Tommy Atkins' mango had higher DMC accumulation rates and shorter periods of fruit growth and development (90–110 d), resulting in similar fruit DMCs at harvest.

Although the average mango DMC was similar between genotypes and growing seasons, there was a high fruit-to-fruit DMC variability at harvest. Considering that mango DMC is an important index of ready-to-eat fruit quality (Saranwong et al., 2004; Subedi and Walsh, 2011; Jha et al., 2012; Nordey et al., 2016; Anderson et al., 2017; Maldonado-Celis et al., 2019; Sung et al., 2019; Hor et al., 2020; Liguori et al., 2020), identifying the factors determining the fruit-to-fruit DMC variability is important to establish approaches that favor more homogeneous mango DMC and therefore quality to consumers.

Table 3
Consumer acceptability for overall satisfaction, flavor, appearance, texture, and sensory scores for the intensity of sweetness, acidity, juiciness and fibrosity of 'Palmer' mangoes produced in the São Francisco Valley, harvested with different dry matter (DM) ranges in April and October and stored at 12 °C until the fruit reached the ready-to-eat stage with flesh firmness ≤ 15 N.

Harvest	DM (g kg^{-1})	Consumer acceptability[a]				Descriptor intensity[b]			
		Overall satisfaction	Flavor	Appearance	Texture	Sweetness	Acidity	Juiciness	Fibrousness
April	100–120	6.5 b[c]	5.6 b	6.9 b	6.4 b	2.3 b	2.1 a	4.4 b	2.2 b
	130–150	7.3 a	7.1 a	7.6 a	7.1 a	4.8 a	2.2 a	4.7 b	2.8 b
	160–180	7.5 a	7.5 a	7.5 a	7.4 a	5.7 a	2.6 a	6.0 a	3.1 a
October	120–130	6.1 b	5.2 b	6.6 b	6.2 b	2.8c	4.0 a	4.9 b	2.9 a
	140–150	7.2 a	7.1 a	7.4 a	7.2 a	4.5 b	3.2 b	5.6 a	2.6 a
	160–170	7.7 a	7.7 a	7.8 a	7.6 a	5.2 a	2.5c	5.9 a	2.6 a

[a] Analysis was accomplished using the nine-points hedonic scale (1 = disliked extremely; 9 = liked extremely).
[b] Analysis was accomplished using a non-strucutated scale with 9 cm (0 cm = low intensity, 9 cm = high intensity).
[c] Means followed by the same letter at each harvest are statistically equal according to the Tukey's test (5%).

Table 4
Consumer acceptability for overall satisfaction, flavor, appearance, texture, and sensory scores for the intensity of sweetness, acidity, juiciness and fibrosity of 'Tommy Atkins' mangoes produced in the São Francisco Valley, harvested with different dry matter (DMC) ranges in April and October and stored at 12 °C until the fruit reached the ready-to-eat stage with flesh firmness ≤ 15 N.

Harvest	DMC (g kg^{-1})	Consumer acceptability[a]				Descriptor intensity[b]			
		Overall satisfaction	Flavor	Appearance	Texture	Sweetness	Acidity	Juiciness	Fibrousness
April	100–110	6.6 b[c]	6.0 b	6.8 b	6.4 a	3.0 b	2.6 b	4.0 b	3.8 b
	120–130	6.8 b	6.3 b	7.0 ab	6.7 a	3.3 b	2.8 b	4.0 b	3.9 b
	140–150	7.0 a	7.0 a	7.5 a	6.8 a	4.4 a	3.2 a	5.1 a	4.0 a
October	110–120	6.1 b	4.8c	7.1 a	5.6c	2.13 b	2.63 b	4.18 b	4.86 a
	130–140	6.6 b	5.6 b	7.2 a	6.2 b	2.62 b	3.96 a	4.42 b	4.19 a
	150–160	7.1 a	6.5 a	7.9 a	6.7 a	4.10 a	4.18 a	5.08 a	4.12 a

[a] Analysis was accomplished using the nine-points hedonic scale (1 = disliked extremely; 9 = liked extremely).
[b] Analysis was accomplished using a non-strucutated scale with 9 cm (0 cm = low intensity, 9 cm = high intensity).
[c] Means followed by the same letter at each harvest are statistically equal according to the Tukey's test (5%).

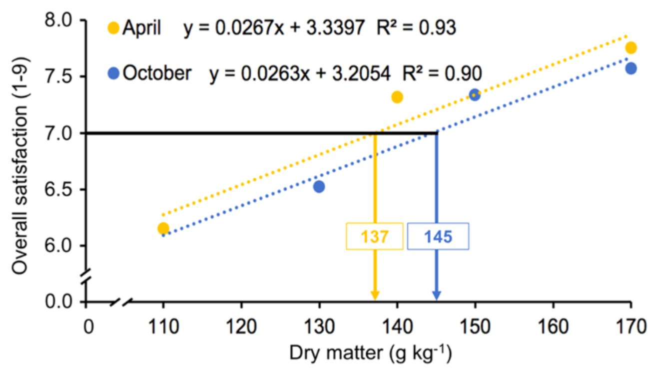

Fig. 5. Recommended dry matter content (DMC) to harvest 'Palmer' mangoes in April (blue arrow) and October (orange arrow) in order to guarantee high fruit quality and consumer acceptance, based on consumer's overall satisfaction (7 = "liked moderately" in the nine-point hedonic scale). Each point represents the average of 100 fruit harvested at each DMC range in April and October. Total = 600 fruit. Overall satisfaction analysis was accomplished by 205 and 140 consumers in April and October, respectively.

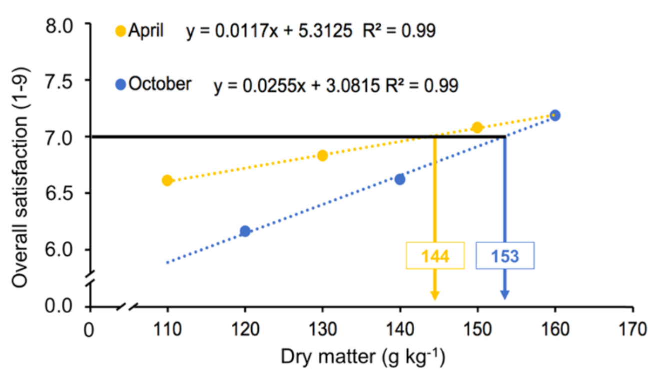

Fig. 6. Recommended dry matter content (DMC) to harvest 'Tommy Atkins' mangoes in April (blue arrow) and October (orange arrow) in order to guarantee high fruit quality and consumer acceptance, based on consumer's overall satisfaction (7 = "liked moderately" in the nine-point hedonic scale). Each point represents the average of 100 fruit harvested at each DMC range in April and October. Total = 600 fruit. Overall satisfaction analysis was accomplished by 205 and 140 consumers in April and October, respectively.

4.2. Possible factors determining fruit-to-fruit DMC variability

Mango ripening is mainly characterized by flesh color changes with reduction in L and °h and increase in C values (Gill et al., 2017). According to our results, 'Palmer' mangoes harvested with higher DMCs had higher L and °h, as well as lower C values in the flesh, indicating a less advanced maturity stage than mangoes harvested with lower DMC in both growing seasons. However, the flesh color differences at harvest were small among fruit with different DMCs, suggesting that all fruit were harvested at similar maturity stages, which is also indicated by the similar fruit SSC and TA at the ready-to-eat ripeness stage. After reaching the ready-to-eat ripeness stage, in contrast to what was observed with 'Tommy Atkins', 'Palmer' mangoes with higher at-harvest DMCs tended to have lower L and °h, as well as higher C values, compared to mangoes with lower DMC, but these differences were also small, again indicating similar maturity stages among fruit with different DMCs.

The DMC has been reported to increase during fruit growth and development on the plant, mainly due to continuous carbohydrate uptake (Falchi et al., 2020). However, the rate of carbohydrate uptake by each fruit depends on its competition with other sink organs, including other fruit; dominance is determined by fruit size and metabolic activity, distance from the source, and source-sink relationship, all of which are affected by the environment and crop management practices (Léchaudel and Joas, 2007; Fischer et al., 2012; Singh et al., 2017; Falchi et al., 2020). In our study, mangoes of each cultivar were harvested according to the commercial recommendations for assessing maturity that are based on fruit shape, lenticel appearance, and ground color (Assis and Lima, 2008), and were later classified into three DMC ranges that represented the variability of fruit DMC in the commercial orchard. Our results with regard to ripening behavior show that fruit of each cultivar produced in each growing season were harvested at similar physiological maturity stages, suggesting that the high variability of fruit DMC content observed at harvest was possibly more affected by the high variability in fruit carbohydrate uptake than by any variability in fruit physiological age. In that case, orchard management practices that reduce fruit competition for carbohydrate uptake, such as reducing crop load and/or increasing plant photosynthetic rates, could help improving fruit carbohydrate uptake, resulting in higher and more homogeneous fruit DMC at harvest (Léchaudel and Joas, 2007; Anderson et al., 2017; Falchi et al., 2020). In addition, it is also possible that fruit with the same physiological age at harvest can have different chronological ages due to different flowering dates, resulting in different fruit DMC accumulation. In that case, orchard management practices aiming to establish a more homogeneous flowering time also could help in homogenizing mango DMC at harvest.

4.3. Mango DMC at harvest and ready-to-eat consumer quality

According to our results, the 'Palmer' and 'Tommy Atkins' mangoes produced during the winter and summer growing seasons that had higher DMCs at harvest also developed higher ready-to-eat% SSC and consumer quality traits, resulting in higher consumer overall satisfaction scores.

Mango fruit contain about 789 g kg^{-1} to 828 g kg^{-1} water, 162 g kg^{-1} to 171 g kg^{-1} total carbohydrate, 3.4 g kg^{-1} to 5.2 g kg^{-1}

ash, 3.0 g kg^{-1} to 5.3 g kg^{-1} lipid, 3.6 g kg^{-1} to 4.0 g kg^{-1} protein, and 8.5 g kg^{-1} to 10.6 g kg^{-1} dietary fiber (Maldonado-Celis et al., 2019). In other words, after removing water from the fruit, 814 g kg^{-1} to 947 g kg^{-1} of the DMC is represented by the total carbohydrates accumulated during growth and development (Maldonado-Celis et al., 2019). Sucrose is the main substrate for synthesis of other carbohydrates in mango. It is produced through photosynthetic metabolism, loaded into the phloem in the leaves and unloaded in the fruit, where it is mainly used to synthesize starch, which is the storage carbohydrate in mango fruit (Lemoine et al., 2013; Ruan, 2014; Li et al., 2020). Later, during ripening, starch is broken down by the action of amylases to produce the soluble sugars that contribute to sweetness; the sugars subsequently provide the carbon backbones of the volatile compounds that contribute to fruit aroma (Fuchs et al., 1980; Peroni et al., 2008; Rahman et al., 2011; Nordey et al., 2016; Maldonado-Celis et al., 2019; Hor et al., 2020; Li et al., 2020; Liguori et al., 2020). Therefore, mango DMC at harvest is an important index of the total carbohydrate content, which is highly represented by the starch that will be the source of the soluble sugars and volatiles required for ripe mango flavor (taste and aroma) development (Tharanathan et al., 2006; Peroni et al., 2008; Wongmetha et al., 2015; Maldonado-Celis et al., 2019). However, although our study does show a positive and linear relationship between mango DMC at harvest and better fruit flavor and consumers' overall satisfaction, determining the minimum fruit DMC that will guarantee good fruit flavor and consumers' positive acceptance is an important step to establish mango quality standards that can be used to classify fruit at harvest based on consumer quality. In addition, these mango quality standards can also be used as a reference index to improve crop management practices in order to produce more mangoes with higher consumer quality.

4.4. Minimum mango DMC at harvest to guarantee positive consumer acceptance

The recommendation of the minimum mango DMC at harvest to guarantee positive consumer acceptance was based on the analyses of consumers' overall satisfaction with the fruit, which considers all desirable quality traits expected by consumers. The results obtained suggest that both of these mango cultivars can have 8.0–9.0 g kg^{-1} lower fruit DMC at harvest in April, compared to October, which is possibly due to the orchard environmental effect on carbohydrate allocation in the fruit before and after harvest. This seasonal effect implies that there are other factors not directly related to DMC that also contribute to consumer acceptability of mango fruit. These results agree with other studies suggesting that DMC alone is not always a strong predictor of mango eating quality, because the production site and/or environmental conditions can also affect other fruit traits that determine the final fruit quality (Hofman et al., 1997; Léchaudel and Joas, 2007). In that case, the required DMC to harvest mangoes should follow the location and seasonal recommendations.

The minimum mango DMCs required to guarantee positive consumer acceptance are similar to the DMCs recommended to harvest 'Kensington Pride' (150 g kg^{-1}), 'R2E2' (130 g kg^{-1}), 'Calypso' (150 g kg^{-1}), and 'Honey Gold' (150 g kg^{-1}) mangoes in Australia (Australian Mango Industry Association, 2015).

In a study conducted in the United States, different mango cultivars imported from different countries were purchased in the local market and subjected to fruit DMC and consumer analyses (González-Moscoso, 2014). According to that study, the minimum mango DMC required to guarantee positive consumer acceptance was 144 g kg^{-1} for 'Ataulfo' from Brazil; 130 g kg^{-1} for 'Tommy Atkins', 123 g kg^{-1} for 'Haden', 169 g kg^{-1} for 'Ataulfo', and 150 g kg^{-1} for 'Kent' from Mexico; 167 g kg^{-1} for 'Francis' from Haiti; 120 g kg^{-1} for 'Kent' from Peru; 130 g kg^{-1} for 'Tommy Atkins' from Guatemala; and 110 g kg^{-1} for 'Tommy Atkins' from Ecuador (González-Moscoso, 2014). Although our study suggests that mango DMC remains constant during ripening, commercial postharvest conditions can vary greatly, which can potentially affect the water/total carbohydrate ratio in the fruit, reducing the precision of the DMC as a consumer quality prediction index when the DMC is measured after storage and transport. This probably explains why the relationship between DMC at harvest and ready-to-eat SSC was higher in our study (R^2 =0.92), compared to the study conducted using mangos obtained after they had reached the final market (R^2 =0.72) (González-Moscoso, 2014). Therefore, the minimum DMC should be determined at harvest for each cultivar, growing season, and production location and later used to determine the harvest maturity and to classify harvested mangoes based on consumer quality. The minimum DMC also could be used to establish orchard management practices to manipulate fruit DMC accumulation and consumer quality prior to harvest through irrigation, pruning, thinning, and other crop management strategies (Léchaudel and Joas, 2007; Fischer et al., 2012; Anderson et al., 2017; Singh et al., 2017; Falchi et al., 2020).

5. Conclusions

Regarding our hypothesis that the minimum mango DMC required to achieve high consumer quality and acceptance is highly affected by the cultivar and climatic/seasonal growing conditions, we conclude that this is not the case. Firstly, the minimum mango DMC required to achieve high consumer quality and acceptance was only weakly related to cultivar and climatic/seasonal growing conditions. In addition, the minimum mango DMC difference between cultivars was only 7 g kg^{-1} and 8 g kg^{-1} for fruit produced during the summer and winter growing conditions, respectively. And the minimum mango DMC difference between growing seasons was only 8 g kg^{-1} and 9 g kg^{-1} for 'Palmer' and 'Tommy Atkins' mangoes, respectively.

'Palmer' and 'Tommy Atkins' mangoes produced during the summer and winter growing seasons in the São Francisco Valley in Brazil that have higher DMC at harvest develop higher SSC during ripening.

In order to guarantee that consumers will be satisfied with the flavor of 'Palmer' or 'Tommy Atkins' mangoes, the fruit must be harvested with a minimum of 137 g kg^{-1} and 145 g kg^{-1} or 144 g kg^{-1} and 153 g kg^{-1} DMC when produced during the summer and winter growing seasons, respectively.

CRediT authorship contribution statement

Sérgio Tonetto de Freitas: Conceptualization, Methodology, Formal snalysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Ítala Tavares Guimarães**: Methodology, Formal analysis, Investigation, Data curation, Writing – original draft. **João Claudio Vilvert**: Methodology, Formal analysis, Investigation, Data curation. **Marcelo H Amaral**: Methodology, Formal analysis, Investigation, Data curation, Writing – review & editing. **Jeffrey K. Brecht**: Conceptualization, Writing – review & editing, Visualization. **Aline Telles Biasoto Marques**: Methodology, Formal analysis, Investigation, Writing – review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the mango grower Agropecuária Roriz Dantas (AGRODAN), Belém do São Francisco, PE, Brazil for the financial support, the Brazilian National Council for the Scientific and Technological Development (CNPq), Brasília, DF, Brazil for the Research Productivity scholarship granted to the corresponding author, as well as

the Fundação de Amparo à Ciência e Tecnologia do Estado de Pernambuco (FACEPE), Recife, PE, Brazil for the master's degree scholarship.

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