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Assessment of fruit ripening status and mass loss thresholds in cactus pear cultivars undergoing room-temperature storage

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Abstract. Cactus pear fruit (*Opuntia* spp.) is an increasingly popular exotic fruit grown in arid and semi-arid regions of Mexico and around the world. This fruit has gained global interest because of its nutritional value, human health benefits, and contribution to food security in marginalized regions. Cactus pear is a non-climacteric fruit; therefore, it is either harvested at the color break (veraison) or ripe fruit (ready-to-eat) stage, depending on the intended market. However, previous postharvest studies have not examined the combination of fruit ripening stage (FRS) with different fruit mass loss (FML) thresholds. This research work aimed the influence of FRS (veraison or ripe fruit) and FML thresholds (5 and 8%) on some quality attributes of white and pigmented cactus pear fruit stored at room temperature. At harvest, veraison fruit of all cultivars had greater flesh firmness but less total soluble solids, peel dry matter and pulp dry matter than ripe fruit, except in 'Roja Lisa'. The time to reach each FML threshold varied significantly among cactus pear fruit cultivars, indicating each cultivar requires different handling. However, during storage, the FRS at both FML thresholds was similar in all cactus pear fruits, except for Amarilla Olorosa fruit at 8% FML. Fruit decay incidence was not influenced by cultivar, FML, or FRS. After reaching 5% FML, fruit appearance began to deteriorate in all fruits. FML of 8% reduced fruit dimensions, but the other quality attributes responded depending on the cactus pear fruits. In conclusion, postharvest handling during storage depends on the specific cultivar. However, the results indicate that the FML threshold for pigmented cultivars can be set at 5% FML. This information is important for postharvest handling and marketing.

Keywords: *Opuntia* spp.*, fruit quality, storability, shelf life, fruit appearance.*

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Introduction

The cactus pear fruit, known as tuna in Mexico, holds social, economic, and therapeutic value worldwide (Manzur-Valdespino *et al*., 2022). However, few scientific studies have examined its ripening physiology and post-harvest life compared to other climacteric and non-climacteric fruits (Watkins and Nock, 2012; Ramírez-Ramos *et al*., 2015). Cactus pear is a non-climacteric fruit, meaning it is harvested almost at a ripeness stage almost suitable for consumption; however, this process theoretically reduces its shelf life, limiting its marketing to distant national and export markets. As a highly perishable fruit, tuna must be sold within a few days after harvest and storage is rarely used due to lack of infrastructure. However, it can be stored when harvested at veraison (Zegbe, 2020).

This is important because the shelf life and quality of this fruit are influenced by changes in room temperature (Ochoa-Velasco and Guerrero-Beltrán, 2013) and ripeness stage during storage (Ramírez-Ramos *et al*., 2015). Under these conditions, reducing fruit mass loss (FML) is crucial to extend post-harvest life and meet market and consumer standards. In this context, the ripeness stage and FML threshold are key factors in post-harvest handling and marketing. The typical FML threshold for most fruits is ~ 5%, especially for climacteric ones (Kader *et al*., 2002). In contrast, for non-climacteric fruits like tuna, Cantwell (1995) established an FML of 8% for white-pulped fruit to indicate post-harvest deterioration that limits its commercialization and consumption. However, this threshold may not be universally applicable due to significant genetic diversity between white and pigmented fruits and differences in ripeness stage (Ramírez-Ramos *et al*., 2015). Therefore, the objective of this study was to evaluate the effect of FML thresholds at different fruit ripening stages on some fruit quality parameters of white and pigmented cactus pear fruits stored at room temperature. This study hypothesized that the fruit ripening stage would behave similarly to the fruit mass-loss thresholds during room-temperature storage. The fruit mass-loss threshold of 8% suggested for white cactus pear cultivars would not apply to pigmented cultivars.

Material and Methods

Plant material

The experiment was conducted during the 2020 growing season at the Campo Experimental Zacatecas in Calera of Víctor Rosales, Zacatecas, Mexico (22°54’ N; 102°39’ W, elevation 2,197 m). It involved fifteen-year-old plants of Cristalina (*Opuntia albicarpa* Scheinvar; a white-fleshed cultivar), Dalia Roja (*O.* spp.; a red-fleshed cultivar), Amarilla Olorosa (*O.* spp.; a yellow-fleshed cultivar), and Roja Lisa (*O. ficus-indica* (L.) Miller; a red-fleshed cultivar). The plants were trained to an open vase system and spaced 4 × 3 m apart (medium density; 833 plants per hectare). They were managed using local agricultural practices, including drip irrigation, fertigation, cladode pruning, fruit thinning, and weed and pest control when necessary. The orchard soil between plant rows was covered with native grass that was mowed mechanically as needed and weeds within the plant lines were controlled mechanically with a brush cutter.

Fruit sampling, treatments, and experimental design

In these plants, the release of reproductive flower buds occurs gradually, leading to fruit maturity throughout the growing season. Based on the goal of this experiment, the fruit harvest was delayed until the end of August (Northern Hemisphere) to collect fruit at both veraison and ripe stages.

From ten plants of each cactus pear cultivar, 150 fruits were collected randomly around the plants. In the lab, the fruits were separated by the fruit ripening stage, de-thorned, and treated with a solution of copper sulfate (2.5 mL L^{-1}) and chlorine (1%). For each cultivar, two sets of 30 uniform fruits were formed and numbered sequentially, for 5 replicates of 6 fruits. The first batch was used to assess the physicochemical attributes of fruits at veraison (color break) and ripe (ready-to-eat) stages at harvest. The second batch was evaluated at 5% and 8% fruit mass loss (FML) for the two ripeness stages stored at room temperature where air temperature (T) and relative humidity (RH) were recorded hourly with a data logger (model 42276, Ex-Tech, Instruments, Waltham, MA, USA). For fruit veraison and ripe stages, each one had three replicates of five fruits, numbered sequentially. Fruit sample sizes were calculated according to Petersen (1994). The experiment was conducted in a completely randomized design per cultivar (cv.). Cultivars were not compared with each other because of their clear genetic differences.

Fruit quality determination

Briefly, fruit quality attributes were assessed as follows: First, each fruit was weighed on a precision balance (VE-303, Velab, Pharr, TX, USA). Then, equatorial and polar diameters of each fruit were measured using a digital caliper (model SC-6, Mitutoyo Co., Tokyo, Japan). Next, flesh firmness was measured using a penetrometer with an 11.1 mm equatorial-diameter tip and a 10 mm penetration depth (model FT 327, Wagner Instruments, Greenwich, CT, USA) on two opposite sides of the fruit's equatorial region. Several juice drops were collected from each side of the fruit, mixed, and used to determine the total soluble solids concentration, expressed in ºBrix, with a digital refractometer (model PR-32α, Atago Co. Ltd., Tokyo, Japan). Subsequently, each fruit was separated into two tissues, peel and pulp, to measure their dry mass concentration (DMPe for peel and DMPu for pulp). For DMPe, a fresh peel sample was taken using a cork borer (17 mm internal diameter). DMPu samples consisted of composite samples of 25 g of fresh pulp and seeds from three fruits. All DMPe and DMPu samples were oven-dried for two weeks at 60 °C until reaching a constant mass. During storage (≈ 24 °C and 40% RH), FML was recorded weekly by weighing each fruit individually until 5 or 8% of FML was reached. Fruit decay incidence was visually recorded at each sampling date in all cactus pear fruits by discarding infected fruits.

Data analysis

Harvesting data were analyzed using a completely randomized model (CRM). The storage data were analyzed with a CRM with a factorial arrangement of treatments, including two fruit ripening stages (veraison and ripe fruit; FRS) and two fruit mass loss (FML) thresholds (5 and 8%), employing the general linear model procedure in the Statistical Analysis System software (SAS Institute ver. 9.4, 2002-2010, Cary, NC, USA). Treatment means were compared using Fisher's least significant difference test at $p \leq 0.05$. Fruit decay incidence was analyzed with the chi-square test.

Results

Fruit quality attributes at harvest

In cv. Amarilla Olorosa, the fruit quality attributes had no significant differences ($p > 0.05$), except for flesh firmness (FF), total soluble solids concentration (TSSC), and dry mass of peel (DMPe). Ripe fruit had softer flesh, but greater TSSC and DMPe than veraison fruit (Table 1). 'Cristalina' fruits showed similar trends, with TSSC significantly greater in ripe fruit. Dalia Roja followed the same patterns as the previous two cultivars; additionally, ripe fruit had greater fruit fresh mass (FFM), equatorial diameter, and dry mass of pulp (DMPu; Table 2). However, Roja Lisa had no statistical differences between veraison and ripe fruit but had in DMPe.

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Table 1. Comparison of physical sweetness attributes between veraison (color break) and ripeness (ready-to-eat) of Amarilla Olorosa and Cristalina cactus pear fruits at harvest.

Cultivar/fruit ripening stage	FFM (g)	FPeM (g)	FPuM (g)	PD (mm)	ED (mm)	FF (N)	TSSC (%)	DMPe (mg g^{-1} FM)	DMPu (mg g^{-1} FM)
Amarilla Olorosa									
Veraison	127.5a*	64.9a	62.6a	86.2a	54.3a	32.9a	11.9b	107.9b	205.6a
Ripe	124.7a	58.4a	66.3a	82.8a	53.9a	28.5b	13.9a	139.5a	201.1a
LSD	22.0	9.8	13.1	6.7	3.2	1.6	0.6	9.9	7.5
p > F	0.78	0.17	0.54	0.27	0.77	0.0002	0.0001	0.0001	0.2
CV (%)	7.2	9.7	9.2	4.7	3.7	16.0	6.7	9.3	2.9
Cristalina									
Veraison	204.3a	66.9a	137.4a	95.6a	66.2a	30.5a	12.1b	137.9a	167.7a
Ripe	185.6b	59.7a	125.9a	92.0b	63.3a	27.1a	12.8a	148.0a	173.8a
LSD	18.8	8.3	16.4	3.7	3.0	5.9	0.553	13.9	2.3
p > F	0.12	0.17	0.42	0.15	0.14	0.25	0.02	0.08	0.20
CV (%)	14.2	26.1	15.7	6.4	5.8	33.3	8.1	14.4	8.9

*Different lowercase letters within columns indicate a significant difference based on Fisher's test at $p \leq 0.05$. LSD: least significant difference; *p* > F: significance level, and CV: coefficient of variation. FFM: fruit fresh mass; FPeM: fruit peel mass; FPuM: fruit pulp mass; PD: polar diameter; ED: equatorial diameter; FF: flesh firmness; TSSC: total soluble solids concentration; DMPe: dry matter of peel and DMPu: dry matter of pulp of fresh mass (FM).

Table 2. Comparison of physical sweetness attributes between veraison (color break) and ripeness (ready-to-eat) of Dalia Roja and Roja Lisa cactus pear fruits at harvest.

Cultivar/fruit ripening stage	FFM (g)	FPeM (g)	FPuM (g)	PD (mm)	ED (mm)	FF (N)	TSSC (%)	DMPe (mg g^{-1} FM)	DMPu (mg g^{-1} FM)
Dalia Roja									
Veraison	194.8b*	80.3a	114.5b	89.3a	65.5b	24.6a	11.3b	109.3b	134.3b
Ripe	220.7a	78.1a	142.6a	92.6a	68.2a	21.3b	13.0a	134.7a	148.3a
LSD	2.3	2.3	15.9	5.0	2.3	1.3	0.6	7.2	13.6
p > F	0.03	0.51	0.004	0.16	0.03	0.01	0.01	0.01	0.04
CV (%)	10.7	11.0	12.5	5.9	5.0	10.9	5.9	14.0	13.2
'Roja Lisa'									
Veraison	145.3a	59.1a	86.2a	83.4a	58.0a	24.7a	13.2a	143.3b	172.7a
Ripe	154.9a	61.7a	93.2a	86.7a	58.9a	26.8a	13.4a	153.7a	175.0a
LSD	28.4	16.3	19.7	5.9	6.2	2.5	0.7	9.2	16.1
p > F	0.70	0.88	0.58	0.29	0.91	0.15	0.47	0.04	0.97
CV (%)	13.4	16.6	15.3	6.9	4.7	15.7	5.3	9.4	9.6

*Different lowercase letters within columns indicate a significant difference based on Fisher's test at $p \leq 0.05$. LSD: least significant difference; *p* > F: significance level, and CV: coefficient of variation. FFM: fruit fresh mass; FPeM: fruit peel mass; FPuM: fruit pulp mass; PD: polar diameter; ED: equatorial diameter; FF: flesh firmness; TSSC: total soluble solids concentration; DMPe: dry matter of peel and DMPu: dry matter of pulp of fresh mass (FM).

Fruit mass loss threshold among cactus pear cultivars

The fruit of Amarilla Olorosa took two weeks after harvest to lose 5% of mass at room temperature storge, with no significant differences between veraison and ripe fruit (Figure 1A). In contrast, ripe fruit reached the 8% FML threshold before veraison fruit, which needed an additional week of storage to reach this FML threshold (Figure 1B). At 5% FML, veraison fruit showed slight wrinkling on the apical

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part (floral receptacle). This wrinkling became more noticeable at 7 or 8% FML for both FRS (Figure 1C). Additionally, when fruit was processed for quality attributes at 5% or 8% FML, visually, the skin color remained unchanged and the pulp stayed juicy, but it was less sweet than at harvest. Therefore, in general, regardless of the FRS and FML tested here, this cultivar's fruit can still be considered acceptable for consumers and marketing.

The chi-square (χ^2) test of independence concluded that FML and FRS are independent of each other for fruit decay incidence (FDI) (χ^2 = 0.209, p = 0.648; Fisher's exact test p = 0.239). Therefore, the observed FDI was zero at 5% FML and zero or 6.7% for veraison and ripe fruit, respectively, at 8% FML. The FDI began in the basal part of the fruit.

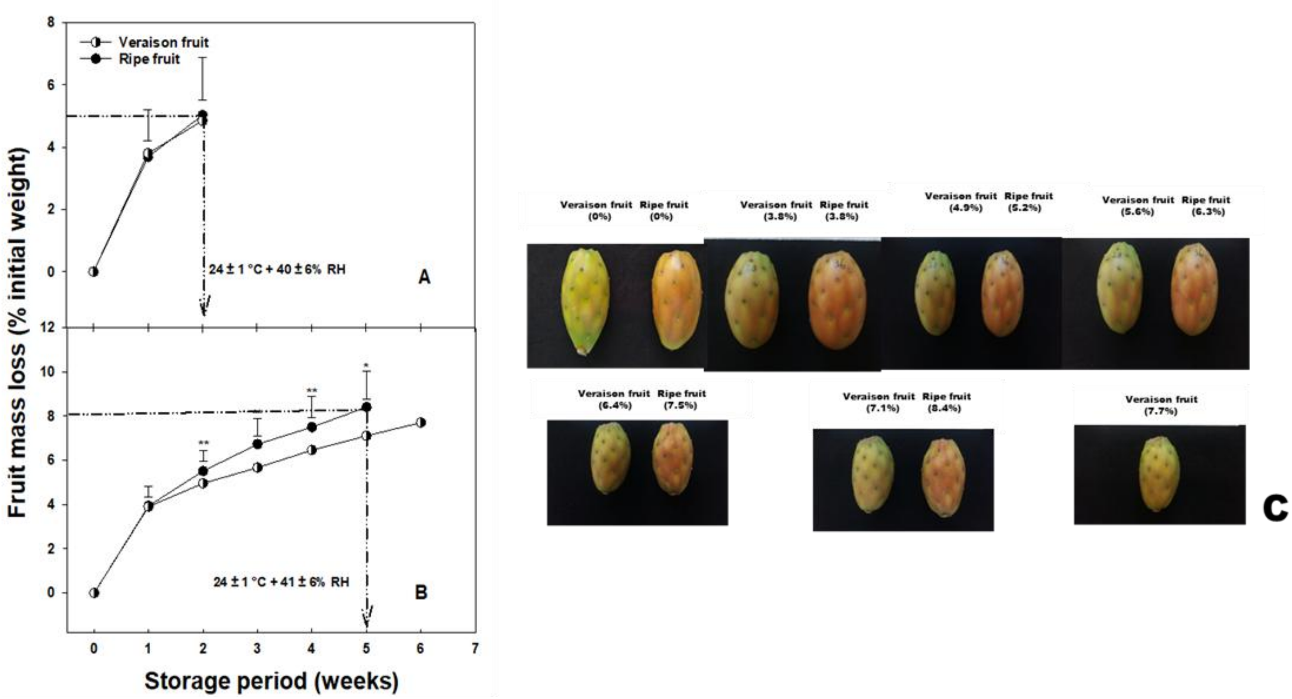

Figure 1. Amarilla Olorosa cactus pear at (A) 5% and (B) 8% cumulative mass loss, harvested at two fruit ripening stages and stored at room temperature. The dash-dot-dot line and arrow on each plot indicate the fruit mass loss threshold. At each sample date, the vertical bars indicate Fisher's least significant difference and the asterisks represent significant differences at $p \leq 0.05$. (C). Physical changes in cactus pear fruit during storage at room temperature caused by fruit mass loss and ripening stages.

The fruit of Cristalina took between three to eight weeks after harvest to lose 5 to 8% of its respective mass at room temperature storage, with no significant differences observed between veraison and ripe fruit at either FML threshold (Figure 2A and B). At 5% FML, veraison fruit showed slight wrinkling on the apical part (floral receptacle). This wrinkling became more noticeable at 8% FML on both the apical and basal parts of the veraison fruit. The fruit skin color remained unchanged during storage (Figure 2C). Additionally, when fruit was processed for quality assessment at 5% FML, visually, the pulp stayed juicy and was sweeter than at harvest. At 8% FML, the pulp was less juicy and sweet, and resembled pasty fruit maybe due to water loss. However, based on our experience, this cultivar's fruit can still be considered acceptable for marketing and consumer preferences over other seasonal fruits.

The FDI at 5% FML was zero for veraison fruit and 6.7% for ripe fruit, and it was 6.7% for both veraison and ripe fruit at 8% FML. The FDI began in the apical and equatorial parts of the fruit.

The fruit of Dalia Roja took between three and 9 weeks after harvest to lose 5 and 8% of its respective mass at room temperature storage, with no significant differences between veraison and ripe fruit at either FML threshold (Figure 3A and B). At 5% FML, the veraison fruit showed slight wrinkling on the apical part (floral receptacle). This wrinkling became more pronounced at 8% FML in the apical and basal parts of veraison fruit and only in the apical part of the ripe fruit. The fruit skin color remained unchanged during storage (Figure 3C). Additionally, when fruit was processed for quality attributes at 5% FML, visually, the pulp was less juicy and sweeter than at harvest. At 8% FML, the pulp was less juicy and sweet than at 5% FML, resembling pasty fruit maybe due to water loss. The FDI at 5% FML was 20% for veraison and ripe fruit, and 6.7 and 20% for both veraison and ripe fruit, respectively, at 8% FML. The FDI began in the apical, basal, and equatorial parts of the fruit.

The fruit of Roja Lisa took between eight and thirteen weeks after harvest to lose 5 to 8% of its respective mass at room temperature storage, with no significant differences observed between veraison and ripe fruit for either FML threshold (Figure 4A and B). At 5% FML, the veraison fruit showed slight wrinkling at the basal part. This wrinkling became more noticeable at 8% FML in the apical and basal parts of veraison fruit, and only in the basal part of the ripe fruit. The skin color of the fruit remained unchanged during storage (Figure 4C). Additionally, when fruit was processed for quality attributes at 5% FML, visually, the pulp was less juicy but still sweeter than at harvest. At 8% FML, the pulp was less juicy and sweet than at 5% FML, resembling pasty and inconsistent pulp (pulp falls apart) maybe due to water loss. The FDI of 5% FML was zero at both FRS, and zero and 27% for veraison and ripe fruit, respectively, at 8% FML. Like Dalia Roja fruit, the FDI started in the apical, basal, and equatorial parts of the fruit.

Fruit quality attributes after reaching the fruit mass loss threshold

In Amarilla Olorosa, there was no significant interaction between FRS and FML for any quality attribute included here, except for FF. At both FRS levels, 5% FML fruits were firmer than those with 8% FML (p = 0.0006; LSD = 2.24 N). The mean values were 22.9 N and 20.5 N for veraison and ripe fruit at 5% FML, and 16.3 N and 17.7 N for veraison and ripe fruit at 8% FML, respectively. The main effect of FRS pointed out that ripe fruit had a smaller equatorial diameter than veraison fruit, while TSSC and DMPe were greater in ripe fruit than in veraison fruit (Table 3). In contrast, FML of 5% resulted in greater fruit peel mass (FPeM) and FF, but lower DMPe, than at 8% FML.

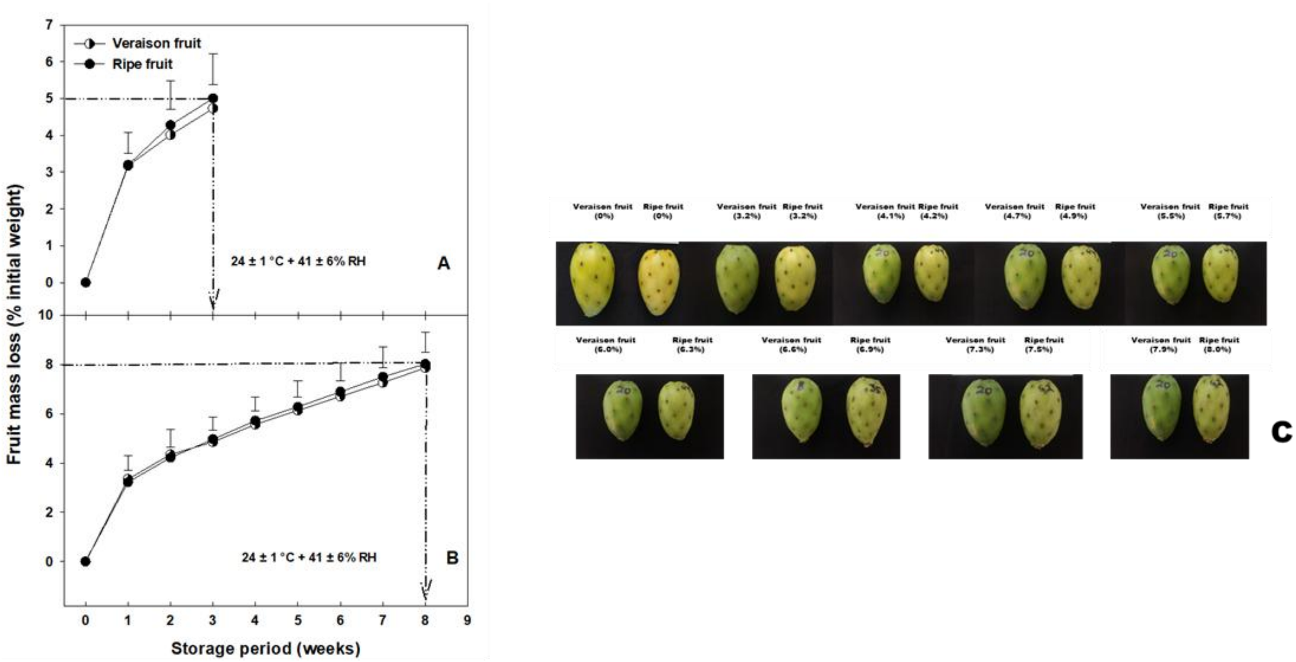

Figure 2. Cristalina cactus pear at (A) 5% and (B) 8% cumulative mass loss, harvested at two fruit ripening stages and stored at room temperature. The dash-dot-dot line and arrow on each plot indicate the fruit mass loss threshold. At each sample date, the vertical bars represent the least significant difference values from Fisher's test at $p \leq 0.05$. (C) Physical changes in cactus pear fruit during storage at room temperature caused by fruit mass loss and ripening stages.

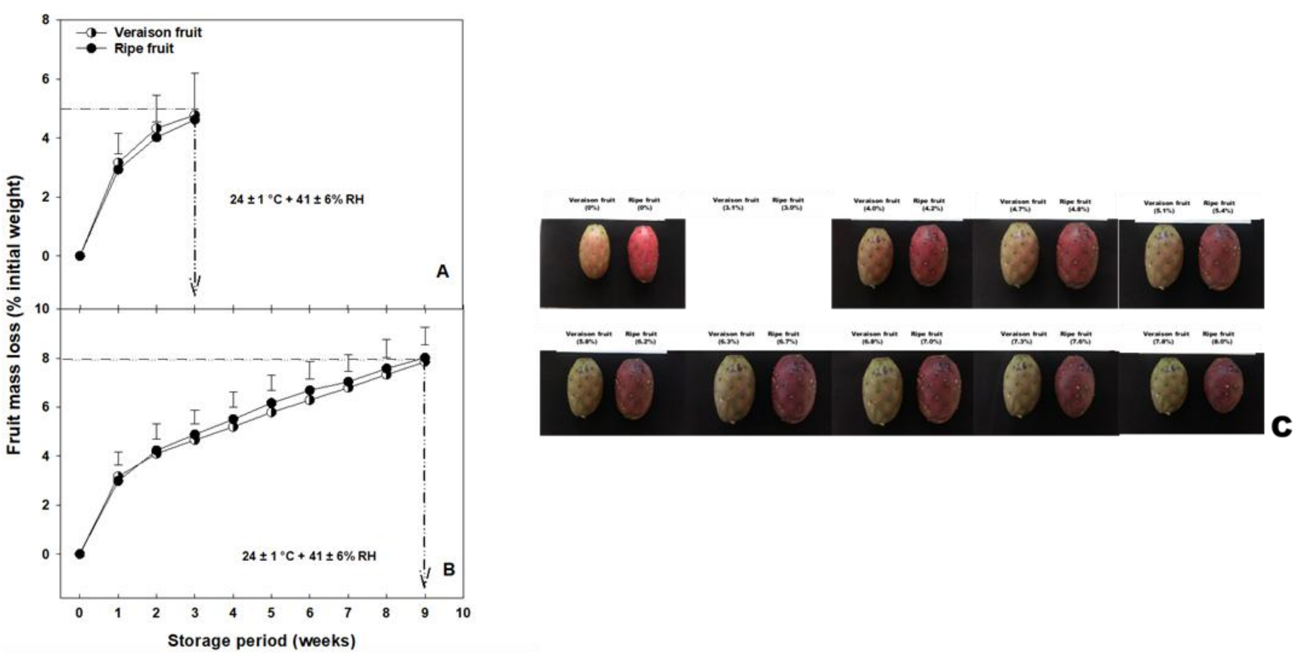

Figure 3. Dalia Roja cactus pear at (A) 5% and (B) 8% cumulative mass loss, harvested at two fruit ripening stages and stored at room temperature. The dash-dot-dot line and arrow on each plot indicate the fruit mass loss threshold. At each sample date, the vertical bars represent the least significant difference values from Fisher's test at $p \leq 0.05$. (C) Physical changes in cactus pear fruit during storage at room temperature caused by fruit mass loss and ripening stages.

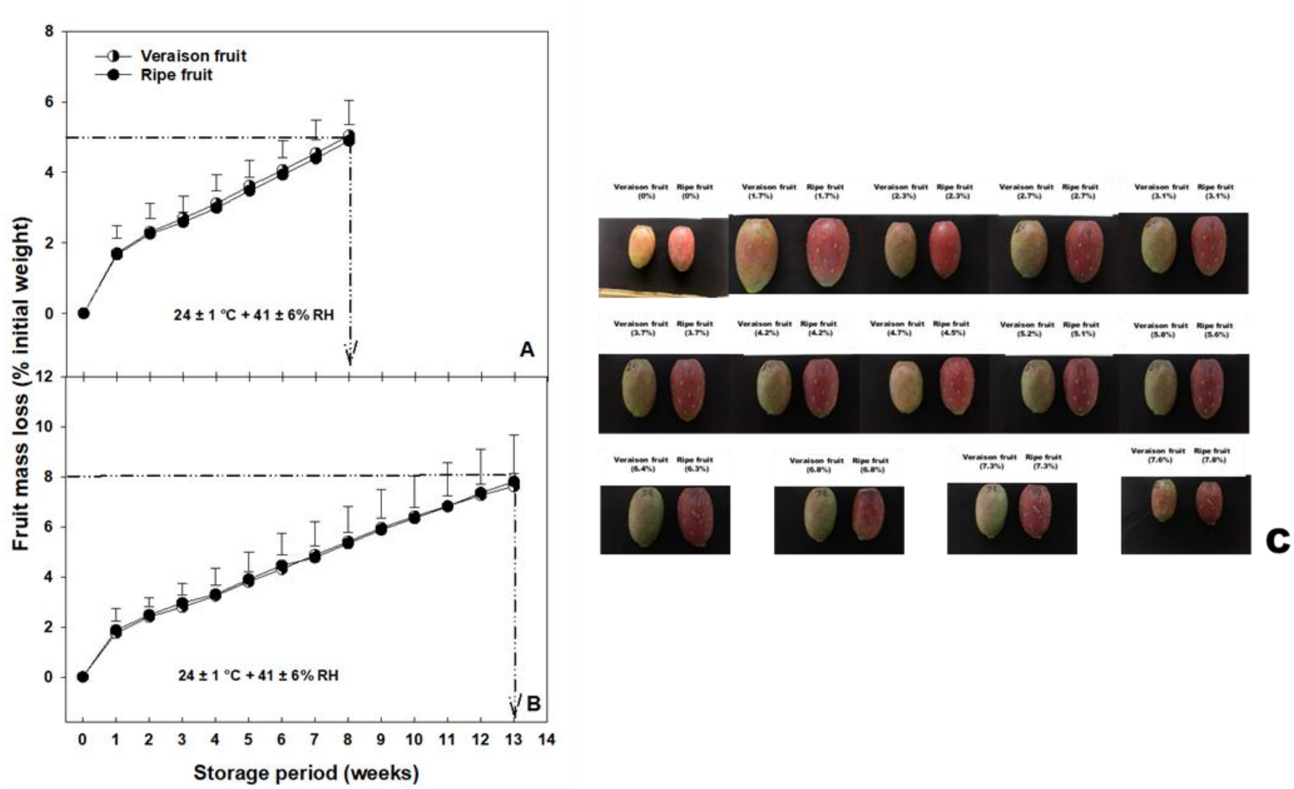

Figure 4. Roja Lisa cactus pear at (A) 5% and (B) 8% cumulative mass loss, harvested at two fruit ripening stages and stored at room temperature. The dash-dot-dot line and arrow on each plot indicate the fruit mass loss threshold. At each sample date, the vertical bars represent the least significant difference values from Fisher's test at $p \leq 0.05$. (C) Physical changes in cactus pear fruit during storage at room temperature caused by fruit mass loss and ripening stages.

Table 3. Changes in some physical and sweetness attributes of Amarilla Olorosa cactus pear fruit, as affected by fruit ripening stage and fruit mass loss after storage at room temperature.

Source of variation	FFM (g)	FPeM (g)	FPuM (g)	PD (mm)	ED (mm)	FF (N)	TSSC (%)	DMPe (mg g^{-1} FM)	DMPu (mg g^{-1} FM)
Main effects									
Fruit ripening stage									
Veraison	120.9a*	40.9a	80.0a	84.9a	53.8a	19.6a	12.8b	133.0b	181.6a
Ripe	119.5a	40.7a	78.8a	84.1a	52.3b	19.2a	14.8a	159.6a	175.4a
LSD	6.7	2.5	4.5	3.9	1.1	1.6	0.4	8.5	5.3
p > F	0.5	0.56	0.51	0.72	0.008	0.48	0.0001	0.0001	0.79
Fruit mass loss									
5%	124.8a	44.3a	80.5a	86.4a	53.3a	21.7a	13.9a	138.0b	188.2a
8%	115.2b	37.0b	78.2a	82.5a	52.8a	16.9b	13.6a	154.3a	168.9a
LSD	6.6	2.5	4.5	3.9	1.1	1.6	0.4	8.5	5.3
p > F	0.01	0.0001	0.26	0.07	0.24	0.0001	0.20	0.002	0.39
CV (%)	14.3	17.8	14.4	6.9	5.9	10.9	5.3	11.7	27.7

*Different lowercase letters within columns indicate a significant difference according to Fisher's test at $p \leq 0.05$. LSD: least significant difference; p > F: significance level, and CV: coefficient of variation. FFM: fruit fresh mass; FPeM: fruit peel mass; FPuM: fruit pulp mass; PD: polar diameter; ED: equatorial diameter; FF: flesh firmness; TSSC: total soluble solids concentration; DMPe: dry matter of peel and DMPu: dry matter of pulp of fresh mass (FM).

In Cristalina, there was no significant interaction between FRS and FML, nor a main effect of FML on the fruit quality attributes included in this study. In contrast, within the main effect of FRS, veraison fruit had greater fruit fresh mass (FFM), fruit peel mass (FPeM), fresh pulp mass (FPuM), polar (PD) and equatorial diameters (ED), and flesh firmness (FF) than ripe fruit, but less TSSC. Even if not significant, ripe fruit tended to have greater DMPe and DMPu than veraison fruit (Table 4).

Table 4. Changes in some physical and sweetness attributes of Cristalina cactus pear fruit, as affected by fruit ripening stage and fruit mass loss after storage at room temperature.

Source of variation	**FFM**	**FPeM** (g)	**FPuM**	**PD**	**ED** (mm)	**FF** (N)	**TSSC** (%)	**DMPe**	**DMPu** ($mg\ g^{-1}$ FM)
Main effects									
Fruit ripening stage									
Veraison	207.1a*	54.4a	152.7a	94.9a	67.5a	23.0a	11.8b	149.1a	155.2a
Ripe	173.5b	44.5b	129.0b	90.0b	62.2b	19.4b	12.8a	157.3a	165.2a
LSD	14.1	4.3	11.4	4.3	1.7	2.0	0.7	16.6	17.2
p > F	0.001	0.001	0.002	0.04	0.0001	0.003	0.01	0.27	0.20
Fruit mass loss									
5%	191.7a	49.7a	142.0a	92.8a	64.9a	21.7a	12.6a	156.5a	163.7a
8%	189.4a	49.3a	140.1a	92.2a	64.9a	20.7a	12.0a	149.7a	156.6a
LSD	14.1	4.3	11.4	4.3	1.7	2.0	0.7	16.6	17.2
p > F	0.855	0.96	0.83	0.78	0.78	0.28	0.10	0.40	0.51
CV (%)	13.6	16.6	14.1	6.5	5.3	20.6	5.9	13.9	6.4

*Different lowercase letters within columns indicate a significant difference according to Fisher's test at $p \leq 0.05$. LSD: least significant difference; *p* > F: significance level, and CV: coefficient of variation. FFM: fruit fresh mass; FPeM: fruit peel mass; FPuM: fruit pulp mass; PD: polar diameter; ED: equatorial diameter; FF: flesh firmness; TSSC: total soluble solids concentration; DMPe: dry matter of peel and DMPu: dry matter of pulp of fresh mass (FM).

In Dalia Roja, there was no significant interaction between FRS and FML for any quality attribute listed here, except for FPeM. The FPeM was lower at both fruit maturity stages at 8% FML than at 5% FML ($p = 0.0001$; LSD = 3.8 g). The average values at 8% FML were 47.2 g and 53.9 g for ripe and veraison fruits, respectively, and 66.6 g and 68.0 g at 5% FML. Conversely, the main effect of FRS was that ripe fruit had the lowest FPeM, but the greatest FPuM, TSSC, and DMPe (Table 5). In contrast, the main effect of FML was that, except for DMPe, the other quality attributes were generally greater in fruit at 5% FML than at 8% FML. No significant mean values were observed for TSSC due to FML (Table 5).

In Roja Lisa, there was no significant interaction between FRS and FML for any of the studied quality attributes. The main effect of FRS significantly affected only TSSC and DMPu. These two fruit quality traits remained higher in ripe fruit than in fruit at veraison. In contrast, the main effect of FML was that fruit at 5% FML maintained greater FFM, FPuM, FF, TSSC and DMPu than fruit at 8% FML (Table 6).

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Table 5. Changes in some physical and sweetness attributes of Dalia Roja cactus pear fruit, as affected by fruit ripening stage and fruit mass loss after storage at room temperature.

Source of variation	FFM (g)	FPeM	FPuM	PD (mm)	ED	FF (N)	TSSC (%)	DMPe ($mg\ g^{-1}$ FM)	DMPu
Main effects									
Fruit maturity stage									
Veraison	199.4a*	61.2a	138.1b	90.0a	67.0a	12.5a	11.9b	135.2b	149.3a
Ripe	213.5a	57.4b	156.2a	92.3a	68.4a	12.0a	13.0a	158.0a	142.2a
LSD	15.9	2.7	15.6	4.7	2.4	1.6	0.91	11.6	30.0
p > F	0.08	0.01	0.03	0.31	0.19	0.55	0.02	0.002	0.70
Fruit mass loss									
5%	222.3a	67.4a	154.9a	94.1a	69.1a	15.2a	12.5a	129.3b	163.1a
8%	188.1b	50.9b	137.2b	87.9b	66.1b	9.1b	12.3a	163.7a	128.4b
LSD	15.9	2.7	15.6	4.7	2.4	1.6	0.91	11.6	30.0
p > F	0.002	0.0001	0.04	0.02	0.03	0.0001	0.74	0.0001	0.06
CV (%)	13.8	14.9	16.1	8.7	5.1	17.9	6.9	13.2	27.7

*Different lowercase letters within columns indicate a significant difference according to Fisher's test at $p \le 0.05$. LSD: least significant difference; *p* > F: significance level, and CV: coefficient of variation. FFM: fruit fresh mass; FPeM: fruit peel mass; FPuM: fruit pulp mass; PD: polar diameter; ED: equatorial diameter; FF: flesh firmness; TSSC: total soluble solids concentration; DMPe: dry matter of peel, and DMPu: dry matter of pulp of fresh mass (FM).

Table 6. Changes in some physical and sweetness attributes of Roja Lisa cactus pear fruit, as affected by fruit ripening stage and fruit mass loss after storage at room temperature.

Source of variation	FFM (g)	FPeM	FPuM	PD (mm)	ED	FF (N)	TSSC (%)	DMPe ($mg\ g^{-1}$ FM)	DMPu
Main effects									
Fruit ripening stage									
Veraison	150.2a*	53.5a	96.7a	83.9a	58.8a	21.1a	11.8b	147.8a	156.2a
Ripe	151.5a	55.5a	96.0a	82.2a	60.7a	22.8a	12.9a	149.2a	170.6a
LSD	9.8	6.3	9.1	5.7	3.3	2.6	0.3	17.1	13.4
p > F	0.63	0.31	0.24	0.23	0.12	0.40	0.0001	0.97	0.06
Fruit mass loss									
5%	161.9a	55.3a	106.7a	85.1a	60.8a	23.3a	12.6a	150.0a	171.7a
8%	136.9b	53.3a	83.6b	80.7a	58.2a	20.1b	11.9b	146.4a	155.1b
LSD	9.8	6.3	9.1	5.7	3.3	2.6	0.3	17.1	13.4
p > F	0.0004	0.84	0.0003	0.05	0.36	0.02	0.01	0.55	0.04
CV (%)	8.3	11.6	10.1	5.3	6.7	16.0	4.7	20.0	4.2

*Different lowercase letters within columns indicate a significant difference according to Fisher's test at $p \le 0.05$. LSD: least significant difference; *p* > F: significance level, and CV: coefficient of variation. FFM: fruit fresh mass; FPeM: fruit peel mass; FPuM: fruit pulp mass; PD: polar diameter; ED: equatorial diameter; FF: flesh firmness; TSSC: total soluble solids concentration; DMPe: dry matter of peel, and DMPu: dry matter of pulp of fresh mass (FM).

Discussion

Fruit quality attributes at harvest

Unlike climacteric fruits, non-climacteric fruits (such as cherries, citrus, grapes, litchi, pomegranate, and strawberries) do not continue ripening after harvest. This is because their low ethylene gas production and respiration rate do not promote ripening (Cherian *et al*., 2014). Therefore, these fruits should be picked when fully ripe (Chervin, 2020). This applies to cactus pear fruit (Cantwell, 1995), as measurable differences in FF, TSSC, DMPe, DMPu, and FPuM were found between veraison and ripe fruits (Tables 1 and 2). Regardless of the cultivar, ripe fruits were softer and TSSC, DMPe, and DMPu

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were greater than in veraison fruits. Therefore, as a non-climacteric fruit, cactus pear fruit ripens on the plant (Alfonso-Salinas *et al*., 2024). At this ripe fruit stage, epidermal degradation occurs, leading to fruit softening and changes in texture and color. Meanwhile, non-water components like sugars, fats, fibers, vitamins, minerals, and other structural and non-structural components increase as water content decreases in the fruit tissues, here reflected in TSSC, DMPe, and DMPu (Pimienta-Barrios, 1990; García-Luis *et al*., 2002; Chervin, 2020). Fruit quality at both FRS stages is crucial for marketing and consumer preferences. Consequently, cactus pear fruit is harvested at color break (veraison) for distant markets and higher prices, while ripe fruit is harvested for local markets at somewhat lower prices. Fruit harvested at the end of the season has increased value regardless of its appearance. On the other hand, compared to ripe fruit, veraison fruit is more resistant to physical damage and pathogen attack during harvest and post-harvest handling than ripe fruit (Pimienta-Barrios, 1990); however, this is dependent on the cultivar, FRS, and FML threshold.

Fruit mass loss (FML) thresholds among cactus pear cultivars

After harvest, the shelf life of fresh products plays a key economic role in marketing to both local and distant markets. Therefore, minimizing fruit mass loss (FML) is essential to delay issues like shriveling, wilting, browning, texture loss, reduced flavor, diminished saleable weight, and aging (Lufu *et al*., 2020). Many pre- and postharvest factors influence FML rates, such as irrigation during cactus pear growth (Melero *et al*., 2022), or, relevant to this study, postharvest environmental conditions like the air temperature (aT) and relative humidity (RH) that surround the fruit during storage until they reach 5% and 8% FML and fruit maturity stage (FRS).

In this study, the aT and RH remained quite stable throughout the experiment (Figures 1 to 4), allowing notable differences among cactus pear cultivars in the timing to reach FML thresholds to be determined; these may be due to genetic differences rather than FRS (Corrales-García *et al*., 2006; Lufu *et al*., 2020). As in the Sanhua plum (Huang *et al*., 2026), FRS did not influence the FML rate of cactus pear fruit. However, Amarilla Olorosa fruit at veraison showed reduced FML at the 8% threshold (Figure 1B), possibly because the fruit was less expanded and had fewer microcracks in the cuticle, reducing water loss. This idea was not studied directly, but compared to the other three cultivars, Amarilla Olorosa had almost no pathogen incidence, which suggests a better lipid coating than the other cultivars included in this study (Taiz and Zeiger, 2006; Huang *et al*., 2026); nevertheless, this hypothesis deserves to be tested.

Regardless of fruit cultivar and storage duration, FML exceeding 5% causes noticeable shriveling (wrinkling) at the fruit's upper and lower ends, contrary to the 8% threshold proposed by Rodríguez-Félix *et al*. (1992) and Cantwell (1995). Nonetheless, regardless of its physical appearance, fruit flavor, and texture, at the end or after the growing season, this fruit can be found minimally processed (peeled) in street markets in some parts of Mexico or offered as an exotic dessert in Europe. This could be true for other cactus pear fruits, except for ‘Dalia Roja’ and ‘Roja Lisa’, due to their pulp consistency (e.g., the fruit pulp looks pasty and falls apart).

Fruit quality attributes after reaching the fruit mass loss threshold

After storage at room temperature, there was no interaction between FRS and FML. Therefore, the main effects of FRS and FML were examined. The main effect of FRS generally maintained the behavior between veraison and ripe fruit observed at harvest, as explained, this is because it is a non-

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climacteric fruit (Watkins and Nock, 2012; Ramírez-Ramos *et al*., 2015). In contrast, except for Cristalina fruit, some measurable reductions in fruit dimensions, including FF, occurred at 8% FML (Tables 3-6). This was due to water loss through transpiration (Maguire *et al*., 1999); meanwhile, cell wall hydrolysis (an enzymatic process) is reflected in FF reduction to varying degrees, depending on the cultivar (Cruz-Hernandez *et al*., 2006), during storage at room temperature (Melero *et al*., 2022). Inconsistent responses of TSSC, DMPe, and DMPu among cultivars due to FML (Tables 3-6) may be controlled genetically, where, as described previously, TSSC could be used for other metabolic processes than respiration in Roja Lisa fruit (Zegbe, 2020). Therefore, we cannot provide a definitive explanation.

The incidence of fruit decay in cactus pear fruits depends on pre-harvest and post-harvest handling (Schirra *et al*., 1999; Dimitris *et al*., 2005; Melero *et al*., 2022). In this study, this issue was not linked statistically to cultivar, FRS, or FML, so the pathogen may have entered through microscopic wounds in the fruit's apical, basal, and lateral parts. The exact cause of the fruit rot was not identify, but it may be related to fungal agents such as *Alternaria alternata*, *Chlamydomyces* spp., *Fusarium* spp., *Macrophomina phaseolina*, and *Penicillium polonicum* (Granata *et al*., 2017). To reduce fruit postharvest losses, further research is needed on this topic.

Conclusions

This study assessed how fruit maturity stage and mass-loss thresholds affect specific quality attributes of white and pigmented cactus pear fruit stored at room temperature (≈ 24 °C and 40% relative humidity). According to the stated hypothesis, this was not fully accepted because the cultivars behaved similarly at both fruit maturity stages during storage at room temperature, except for Amarilla Olorosa (a pigmented cultivar).

The facts from this research can be summarized as follows. At harvest, veraison fruit from all cultivars had greater flesh firmness but less total soluble solids, peel dry matter, and pulp dry matter than ripe fruit, except in Roja Lisa. The time required to reach each fruit mass-loss threshold varied significantly among cactus pear cultivars. Fruit maturity stage did not influence fruit mass loss at either threshold significantly, except for Amarilla Olorosa, where ripe fruit reached the 8% loss threshold sooner. After reaching these thresholds, fruit quality attributes remained consistent with those observed at harvest for both ripening stages. Visual changes in fruit appearance can be seen after 5% loss of fruit mass in all cactus pear fruits. These visual changes were more evident at 8% fruit mass loss. The incidence of fruit decay was not related to fruit mass loss thresholds or ripeness. This straightforward study offers valuable insights for postharvest handling of cactus pear fruit for both domestic and export markets.

ETHICS STATEMENT

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF SUPPORTING DATA

All data generated or analyzed during this study are included in this published article, but are available from the first author on reasonable request.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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AUTHOR CONTRIBUTIONS

Conceptualization, J.A.Z; methodology, J.A.Z.; validation J.A.Z.; formal analysis, J.A.Z. and V.D.G.C.; investigation, V.D.G.C.; resources, J.A.Z.; data curation, J.A.Z. and V.D.G.C.; writing—original draft preparation, J.A.Z.; writing—review and editing, J.A.Z.; visualization, J.A.Z.; supervision, J.A.Z. and V.D.G.C; project administration, J.A.Z.; funding acquisition, J.A.Z. All authors have read and agreed to the published version of the manuscript.

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