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Research Article

Influence of Maturity Stage and Storage Time on Physicochemical and Bioactive Properties of Yellow Pitahaya (*Hylocereus megalanthus*)

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Postharvest handling and storage of yellow pitahaya (*Hylocereus megalanthus*) posed challenges due to the variability in physicochemical and bioactive properties at different maturity (M) stages and over time. This study is aimed at assessing the influence of the M and storage time (T) on the physicochemical and bioactive characteristics of yellow pitahaya. Fruits at three M stages (green, semiripe, and ripe) were collected, stored at 16°C with 85% relative humidity, and evaluated over 20 days (Days 1, 5, 10, 15, and 20). The research analyzed how M and T affected key quality attributes and bioactive components, identifying the M stage that optimized these properties for consumption. Physicochemical changes, as well as chemical composition and antioxidant capacity of 1-day fruit powders, were assessed. Fruit dimensions, moisture, and firmness were mainly influenced by M, while weight loss, pH, soluble solids, and acidity were influenced by T. Color showed significant sensitivity to both factors. Green fruits were the smallest, with the highest firmness and lowest volume, while ripe fruits had the lowest epicarp percentage and thickness. During storage, significant reductions in dimension, volume, epicarp thickness, soluble solids, and acidity were observed, while weight loss, mesocarp + endocarp, color, pH, and M index increased. Chemical composition and bioactive properties varied notably with M stage, with semiripe and ripe fruits exhibiting the most favorable bioactive characteristics. In conclusion, both M and T significantly influenced most physicochemical and bioactive properties of yellow pitahaya, highlighting the semiripe and ripe stages as optimal for harvest, offering practical insights for improving postharvest handling and storage practices.

Keywords: antioxidant capacity; color; firmness; proximal composition; total phenols

1. Introduction

The pitahaya or pitaya belongs to the Cactaceae family, comprising around 125 to 130 genera and 1400 to 1500 species, of which an average of 250 are valued as fruits [1, 2]. Due to its physicochemical, organoleptic characteristics and market acceptance, the species with agronomic, the highest production, and commercial value is the yellow pitahaya (*Hylocereus*

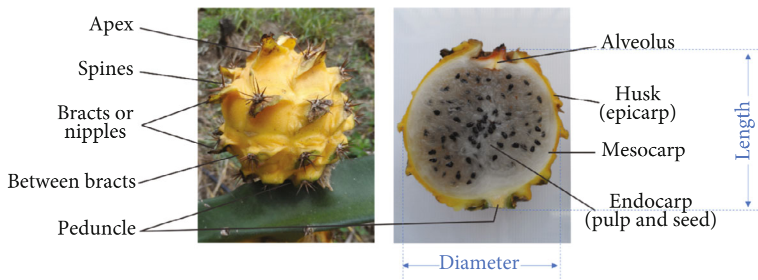

Figure 1: Parts of the yellow pitahaya fruit in the ripe state (*Hylocereus megalanthus*), adapted from Yoplac et al. [3].

megalanthus), which until before 2003 was known as *Selenicereus megalanthus*. At maturity (*M*), yellow pitahaya is characterized by a gnarled, thorny yellow epicarp, while its edible portion consists of the mesocarp and endocarp, which form the white pulp and seeds, as shown in Figure 1 [3–5].

The yellow pitahaya is native to the Andean regions of South America, including Colombia, Venezuela, Bolivia, Peru, and Ecuador [6]. Its optimal growth conditions occur at altitudes between 500 and 1900 m above sea level, with temperatures ranging from 18°C and 25°C, annual rainfall between 1200 and 2500 mm, relative humidity between 70% and 80%, and soil pH values between 5.3 and 6.7 [7].

Yellow pitahaya faces several challenges in both pre- and postharvest stages, including uneven ripening, susceptibility to mechanical damage, and rapid quality deterioration during storage. These issues impact the fruit's marketability and shelf life, presenting difficulties for both producers and retailers. Understanding how the stage of *M* and storage time (*T*) affect the physical parameters and chemical characteristics of yellow pitahaya is essential, as these factors directly influence its quality and consumer acceptance. This knowledge not only optimizes harvesting processes and enhances agricultural practices but also facilitates more effective supply chain planning. Together, these improvements contribute to more efficient, sustainable, and higher-quality production and marketing [6, 8–10]. Sotomayor et al. [11] reported that the average total soluble solid (TSS) content of pitahaya is 20.74°Brix (°Bx), with a titratable acidity (TA) of 0.14 and a pH of 4.86. The color, weight, volume, length, and diameter, among others, change significantly during fruit growth and maturation. Additionally, pitahaya is a good source of minerals (3.47 mg calcium/100 g, 30.2 mg phosphorus/100 g, and 0.55 mg iron/100 g) and contains 8 g/100 g of glucose, 0.5 g/100 g of dietary fiber, and 8 mg/100 g of vitamin C [8, 10, 12–14].

Yellow pitahaya is the only fruit produced on a large scale that contains high levels of betalains [15]. Some studies have focused on betalains, which are rich in antioxidant compounds known to prevent neurodegenerative diseases [5, 15]. Additionally, betalains have demonstrated antimicrobial properties [16]. Research has shown that the pitahaya peel contains higher concentrations of betacyanins and betaxanthins compared to the pulp [9, 17]. Furthermore, the seeds are a valuable source of fatty acids, particularly linoleic acid, which is recognized for its antioxidant activity [13, 18, 19]. Another significant component of pitahaya's chemical composition is water-soluble polysaccharides, which contributed to improved intestinal microbiota health [8, 14, 20].

In fruit management, determining the optimal harvest time is crucial to offering a product with good organoleptic and nutritional quality to the market [21]. Osuna et al. [22] observed that *Hylocereus undatus* Haw. fruits harvested at semiripe and ripe *M* retained higher TSSs than those harvested at the green *M* stage, though they experienced rapid decline in acidity. Rodríguez et al. [23] recommended that yellow pitahaya should be harvested at an advanced *M* stage and stored between 8°C and 19°C.

Most research has focused on the physicochemical and nutritional characteristics of *H. undatus* and *Hylocereus polyrhizus* at different stages of development [1, 24, 25], while few studies have examined the changes occurring during storage. Yellow pitahaya (*H. megalanthus*) is commercially valued for its organoleptic and bioactive properties. Although research exists on related species, the impact of *T* on fruit quality has often been overlooked. This study is aimed at filling the gap by evaluating the influence of *M* stage and *T* on the physicochemical characteristics of yellow pitahaya (*H. megalanthus*) as well as the effect of fruit *M* on the bioactive properties of fruit powder. To the best of our knowledge, this is one of the first studies to assess both the bioactive components and physicochemical properties of yellow pitahaya in relation to *M* stages and storage duration. This highlights the novel contribution of this research to the existing body of literature on pitahaya fruit quality.

2. Material and Methods

2.1. Materials. Yellow pitahaya (*H. megalanthus*) fruits were obtained from the "Don Machamo" farm, located in Matiaza Rimachi, Valera District, Bongará Province, Amazonas Region, Peru (latitude (S) 6°02′48″ S, longitude (W) of 77°55′57″). The fruits were cultivated under the tutor system and manually harvested using scissors, following the removal of thorns. A simple random sampling method was applied to ensure representative fruit selection from different parts of the field, capturing the diversity of the entire harvest.

The plants were 3 years old at the time of fruit collection. The fruits were classified into different *M* stages based on the yellowness of their shell: green (25%–50%), semiripe (50%–75%), and ripe (75%–90%) (see Day 1 in Figure 2), according to the methodology established by the Instituto Ecuatoriano de Normalización [26]. After classification, the fruits

Figure 2: Photograph of the yellow pitahaya fruits collected at three maturity stages (green, semiripe, and ripe) after 1, 10, and 20 days of storage.

were transported in harvest crates to the laboratory at the Toribio Rodríguez de Mendoza National University (UNTRM) and stored at 6°C for 24 h [9]. They were then washed with water, disinfected in a sodium hypochlorite solution (NaClO) at a concentration of 95 mg/L; rinsed in sterile water; and subjected to further washing, disinfection, and rinsing at 6°C for 1 min. Afterward, they were air-dried at ambient temperature and stored at 16°C with 85% relative humidity for a period of 20 days, following the recommendations of Hernández-Ramos et al. [9] and Rodríguez et al. [23]. The physical and chemical characteristics of the fruits at different stages of M were evaluated after 1, 5, 10, 15, and 20 days of storage. Five replicates were prepared for each treatment.

The chemical composition and bioactive properties were evaluated using powders obtained from fruits collected at different stages of ripeness, following 1 day of storage. The powders were produced by drying mesocarp and endocarp (pulp and seed) of the fruits at 40°C for 72 h in an oven. This low drying temperature was chosen to prevent the degradation of bioactive and biochemical compounds. After drying, the fruits were manually crushed using a mortar and pestle. Three replicates were prepared for each treatment.

2.2. Analyses of the Fruits. The physical and chemical characteristics of the yellow pitahaya fruits were evaluated with five replicates ($n = 5$) for each M stage (treatment).

2.2.1. Physical Characteristics. Length, diameter, epicarp thickness, mesocarp thickness, and endocarp thickness were measured using a manual vernier caliper (Vogel, Germany), as described by Velásquez-Cedeño et al. [27] and Yoplac et al. [3]. For the different thickness measurements, the fruits were previously longitudinally cut (from the apex to the pedicel); then, the average ($n = 5$) was calculated. The weights of fruit, epicarp, mesocarp, and endocarp were measured with an Ohaus analytical balance (Model PA224C, United States) with an accuracy of ±0.0001 g; the epicarp percentage from the total weight was calculated, as well as the mesocarp + endocarp percentage [3, 26–28]. Fruit epicarp color ($L*$, $a*$, b^*, and total color difference ΔE, calculated with Equation (1), using the CIELab* system) was measured with a CR-400 colorimeter (Konica Minolta Co. Ltd., Osaka, Japan) [3].

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

where $\Delta L*$, $\Delta a*$, and $\Delta b*$ are the differentials between the color parameter of the samples and the color parameter of a standard white cardboard used as a fruit backing.

Firmness was measured using a Sh&WRange penetrometer (Model GY-4, China) equipped with a 4.5-mm tip [27]. The volume was measured in a 1000-cm^3 beaker, by the displacement method [3]. The moisture percentage was measured with an A&D MX-50 (Japan) digital halogen thermobalance with an accuracy of 0.01% [29].

For the measurement of length, diameter, volume, epicarp color, and weight loss, the same fruits were used on all evaluation days. Firmness; humidity; epicarp, mesocarp, and endocarp thickness; epicarp, mesocarp, and endocarp content; and different fruits were used.

2.2.2. Chemical Characteristics. The pH of the fruit juice was measured using the potentiometric method, with a Hanna pH meter (Checker, Romania), following Method 981.12 [29]. The TSS content was measured taking into account Refractometric Method 932.12 [29], using an Abbe refractometer (Vee Gee, C10, United States); the results were expressed in °Brix. The TA was performed using the titration method, following Method 942.15 [29]; the results were calculated considering citric acid as a reference and expressed as percentage (grams of citric acid/100 g). The maturity index (MI) was obtained from the ratio between TSS and acidity [27]. For each M stage and T, five repetitions were used.

2.3. Analyses of the Fruit Powder. The chemical composition, total phenol content (TPC), and antioxidant capacity of the yellow pitahaya fruit powders were evaluated with three replicates ($n = 3$) for each M stage (treatment).

2.3.1. Chemical Composition. The chemical composition was analyzed following the AOAC [29] methods for moisture content (No. 925.09), protein (No. 979.09), total ashes (No. 923.03), lipid (No. 920.39), crude fiber (No. 962.09), and carbohydrates by difference. The results were expressed as gram/100 g in dry matter (g/100 g DM).

2.3.2. TPC. The TPC was evaluated following the methodology proposed by Char et al. [30] with modifications: 1 g of powder was weighed and 9 mL methanol:water (1:1) was added, mixed and crushed manually in a mortar for 4 min, poured into a 15-mL falcon tube covered with aluminum, and centrifuged at 3000 rpm (9960 *g*) for 30 min; the supernatant was recovered and filtered through Whatman No. 40 paper. TPC analysis was performed with the addition of the Folin–Ciocalteu reagent. The absorbance of the samples at 660 nm was measured with a UV-Vis spectrophotometer (Genesys 10S VIS, Thermo Scientific, United States). The results were expressed as equivalent milligrams of gallic acid per gram (mg GAE/g).

2.3.3. Antioxidant Capacity. The 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical cation scavenging capacity of the methanolic extract was evaluated according to Char et al. [30]. The absorbance was measured at 515 nm in a UV-Vis spectrophotometer (Genesys 10S VIS, Thermo Scientific, United States), using methanol as blank. Results were expressed as Trolox equivalent milligrams per gram (mg TE/g).

2.4. Statistical Analysis. To evaluate the effects of the *M* stage and *T*, on the physical and chemical characteristics of the fruit, the data were analyzed using two-way analysis of variance (ANOVA). Additionally, to assess the influence of *M* stage on fruit color coordinates, chemical composition, and bioactive properties of the fruit powder, as well as the effect of *M* stage or *T* on the physical and chemical characteristics, one-way ANOVAs were conducted. Prior to the ANOVAs, the normal distribution of the data was verified, and logarithmic transformation was applied to the fruit volume response. In cases where significant differences were observed ($p < 0.05$), Fisher's least significant difference (LSD) test at a 95% confidence level was applied. However, for the analysis of the effect of the *M* stage on the physical and chemical characteristics on each evaluation day, the Tukey test was used, also at a 95% confidence level.

All analyses were performed using the statistical program STATGRAPHICS Centurion (Statpoint Technologies Inc., Warrenton, Virginia, United States). The means and standard deviations were calculated using the Excel program (Microsoft, Redmond, Washington, United States).

3. Results and Discussion

3.1. Physical Characteristics of the Fruits During Storage. Figures 3 and 4 and Tables 1 and 2 present the results of the physical characteristics of yellow pitahaya fruits harvested at different *M* stages and assessed at various *T*. The two-way ANOVA results, provided in Table S1, indicated significant differences among *M* stages for all physical characteristics of the fruit ($p < 0.05$), except for ΔE. Similarly, *T* significantly affected most characteristics, except of diameter, firmness, and mesocarp + endocarp thickness. The interaction between *M* and *T* was significant only for color parameters and weight loss (Table S1), although the latter was of lesser importance. The *M* stage had a significant influence on all the fruit's physical characteristics, with the exception of ΔE , while *T* did not significantly impact diameter, firmness, moisture, or mesocarp + endocarp thickness (Table 2 and Table S1).

Fruit length ranged from 88 to 98 mm, diameter from 63 to 75 mm, and firmness from 9 to 12 N (Figure 3). These length values exceed those reported by Vásquez-Castillo et al. [7] for the Palora variety (83 and 66 mm). Similarly, the diameter and firmness values were higher than those reported by Vera et al. [31] for yellow pitahaya at different hardening stages, where diameter ranged from 48 to 59 mm and firmness from 2 to 5 N. Firmness varied significantly across *M* stages (Table S1), consistent with the findings of Sotomayor et al. [11].

Fruit volume was significantly affected by both *M* stage and *T* (Table S1). In the later stages of evaluation (15 and 20 days), *M* stage had a significant influence on volume ($p < 0.05$), with green fruits showing the lowest values (216.4–229.5 cm^3), while ripe fruits exhibited the highest volumes (262.7–273.4 cm^3; Figure 3). These volumes are lower than those reported by Yoplac et al. [3] for yellow pitahaya, which ranged from 300 to 350 cm^3. Fruit volume is primarily determined by fruit weight, variety, and size [6, 8].

Weight loss increased over time, and by Day 20, *M* stage significantly influenced this variable ($p < 0.05$), with green fruits exhibiting the highest weight loss at 17.8% (Figure 3). Similar trends were reported by Ortiz and Takahashi [32]. This weight loss is likely attributed to water loss through evaporation, fruit permeability to water vapor, respiration rates, and biochemical changes, which are more pronounced in green fruits [33, 34].

The *M* stage significantly influenced moisture content (Table S1), with green fruits exhibiting higher moisture levels than ripe fruits. These moisture values are consistent with those reported by Cañar [35] for commercial yellow pitahaya (84.80%). Moisture content has practical implications for fruit quality, shelf life, and transportation, making it a critical factor in the management and marketing of pitahaya fruits [8].

Figure 4 illustrates the thickness and content of the different structures of yellow pitahaya fruit at various *M* stages, evaluated over a period of 20 days. From Day 1 to Day 15, green and semiripe fruits showed significantly greater epicarp thickness ($p < 0.05$), ranging between 2.5 and 3.5 mm. However, by Day 20, all *M* stages displayed similar values for this variable ($p > 0.05$), varying between 1.8 and 2.2 mm. Regarding mesocarp and endocarp thickness, significant differences ($p < 0.05$) were observed on all evaluation days except Day 10, with ripe fruits showing the highest values, ranging from 69.7 to 70.5 mm, while green fruits had the lowest values, between 60.3 and 61.1 mm.

As expected, green and semiripe fruits consistently showed the highest percentage of epicarp throughout the evaluation period, with a marked decrease over time, ranging from 52.1% to 32.8%. In contrast, ripe fruits exhibited a lower epicarp content, which decreased during storage from 31.2% to 23.7% ($p < 0.05$). Conversely, ripe fruits consistently had the highest mesocarp + endocarp content, which increased during storage from 68.3% to 76.3%. Green and semiripe fruits, although lower in mesocarp + endocarp content, also showed an increase from 48.0% to 67.2% ($p < 0.05$). This trend aligns with findings by Magalhães et al. [24] and Ortiz and Takahashi [32] for red-pulp and yellow-pulp pitahaya. These changes are driven by biochemical alteration during fruit ripening, leading to thinner peels and a greater edible portion [6, 8].

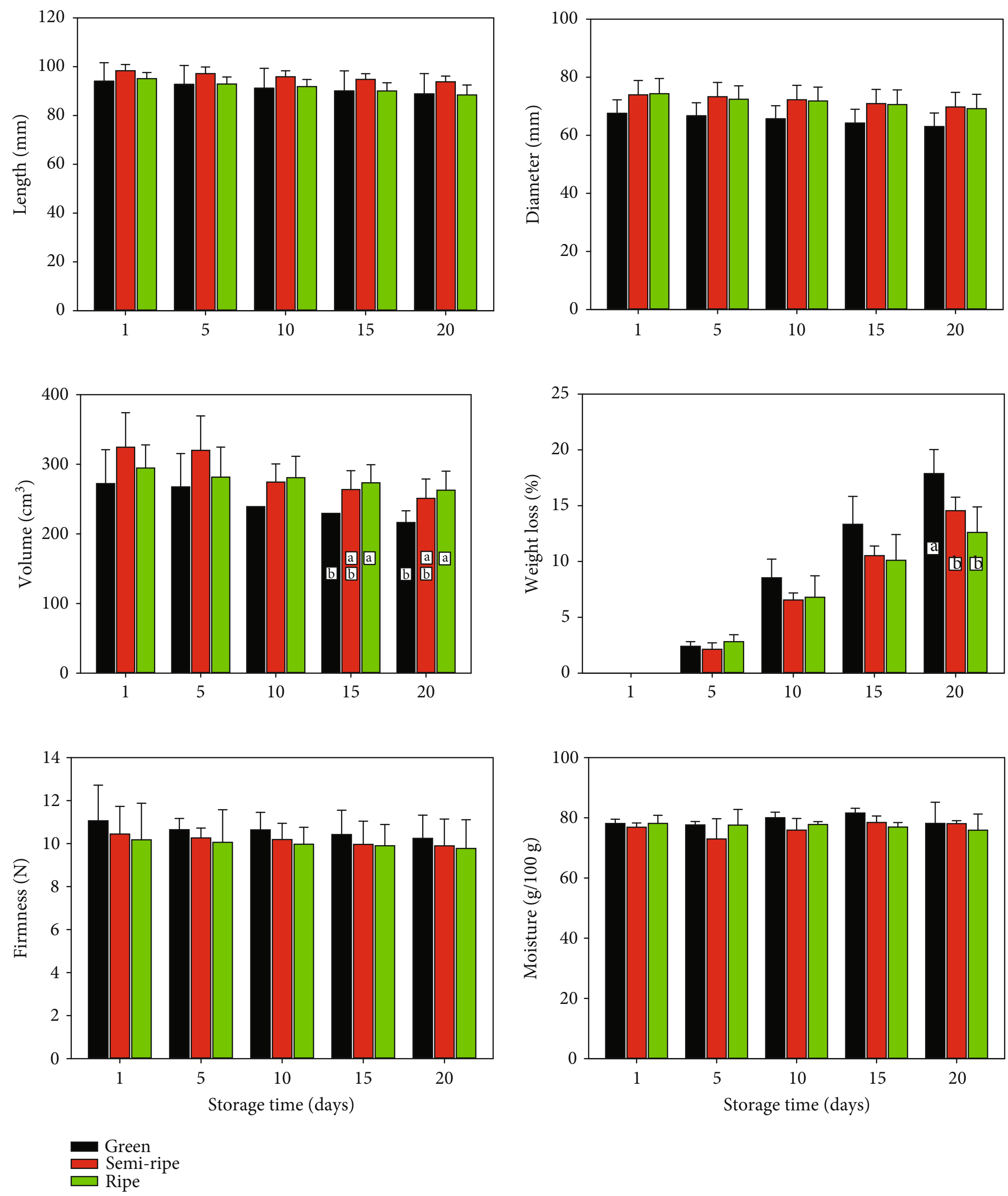

Figure 3: Physical characteristics and moisture content of yellow pitahaya fruits (*Hylocereus megalanthus*) collected at three maturity stages during 20 days of storage. Bars represent standard deviation ($n = 5$). Different letters on each evaluation day indicate statistically significant differences according to the Tukey test ($p < 0.05$), for each maturity stage (MS).

The epicarp color values are shown in Table 1. *M* stage significantly influenced the $L*$ coordinate only up to Day 15 ($p < 0.05$), while *T* affected the $L*$ values of green and semiripe fruits ($p < 0.05$). Ripe fruits exhibited higher $L*$ values (61–65) compared to green and semiripe fruits (43–62), though $L*$ values converged between 62 and 64 by Day 15 across all *M* stages. The $a*$ coordinate increased significantly during storage ($p < 0.05$) for all *M* stages, with ripe fruits showing higher values (5.8–12.2) than green and semiripe fruits (−6.4–9.5). This increase in $a*$ over time reflects the reduction in green color (Table 1, Figure 2). The $b*$ coordinate was significantly influenced by *M* stage only on Days 1 and 5, with $b*$ values increasing during the first 10 days for green and semiripe fruits ($p < 0.05$), indicating the appearance of the yellow peel color (Figure 2). Ripe fruits maintained consistently high $b*$ values (39.9–44.1), while green and semiripe fruits increased from 16.0 to 44.0. The $\Delta E*$ parameter followed a similar trend to the $b*$ values. These findings on pitahaya peel color are consistent with those reported by Otálora et al. [36] and Yoplac et al. [3].

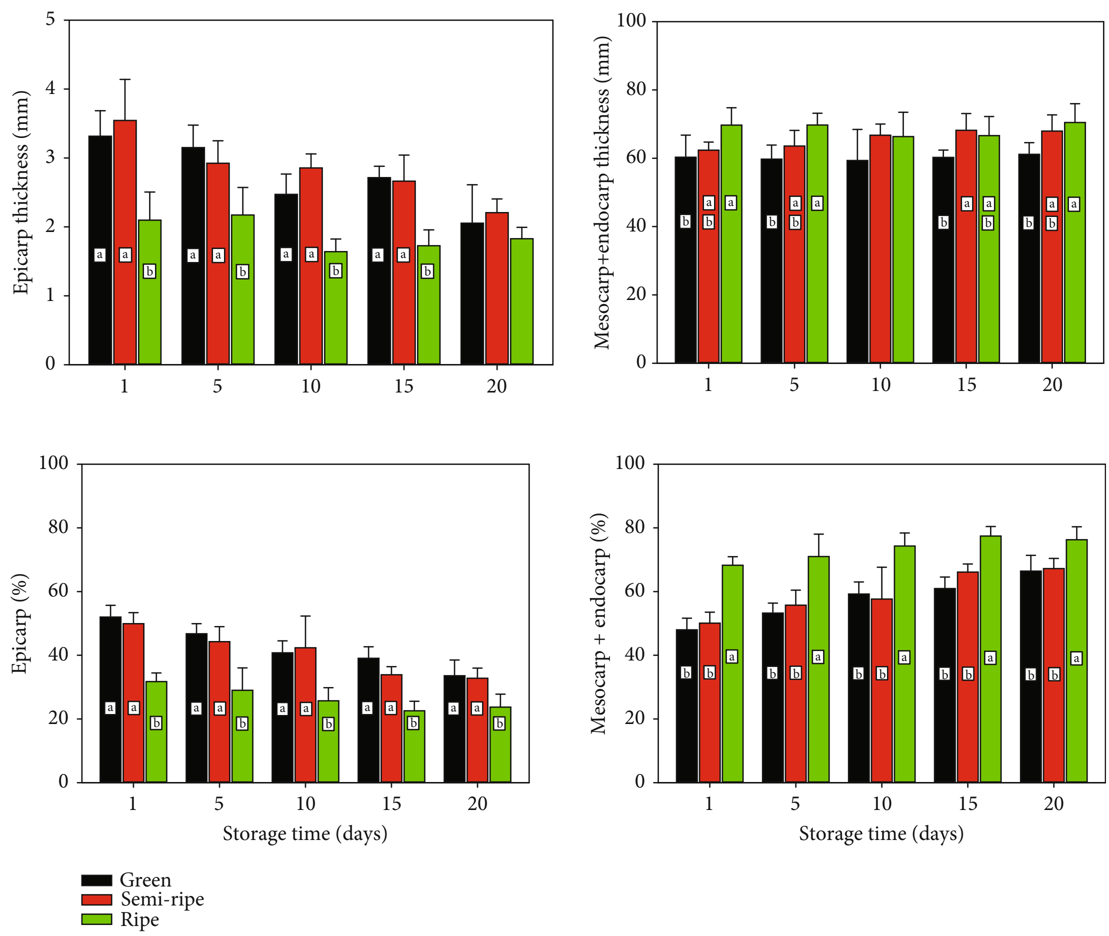

Figure 4: Epicarp and mesocarp + endocarp thickness and content of yellow pitahaya fruits (*Hylocereus megalanthus*) collected at three maturity stages during 20 days of storage. Bars represent standard deviation ($n = 5$). Different letters on each evaluation day indicate statistically significant differences according to the Tukey test ($p < 0.05$), for each maturity stage (MS).

These color changes primarily result for ripening processes, including chlorophyll degradation and the synthesis of new pigments, mainly betalains. As *M* and *T* progress, the reduction in chlorophyll and the accumulation of carotenoids gradually turn the peel from green to yellow [9].

3.2. Chemical Characteristics of the Fruits During Storage. The chemical composition results of the fruits are shown in Figure 5. All parameters were primarily influenced by the *T*, while the *M* stage had a significant effect only on pH, although the interaction between the *M* and *T* was of minor importance (Table S1). As yellow pitahaya, like other pitahaya varieties, is a nonclimacteric fruit, the ripeness stage plays a relatively smaller role in altering its chemical composition compared to *T*, which plays a more critical role in inducing changes in chemical attributes [9].

When evaluating the effect of *M* stages on pH across different evaluation days, significant differences ($p < 0.05$) were observed only on Days 5 and 10. On Day 5, ripe fruits had the highest pH value at 4.7, whereas on Day 10, green fruits exhibited the highest pH value at 4.7 (Figure 5).

When analyzing pH globally for each factor (Table 2), both factors influenced this variable. Ripe fruits exhibited higher pH levels (4.7), compared to green and semiripe fruits (4.6 and 4.5, respectively). Moreover, pH values increased throughout the storage period, ranging from 4.3 to 4.9. This gradual increase in pH during storage aligns with previous research on yellow pitahaya, where both ripeness stage and *T* were key factors in pH fluctuations [10, 11, 37].

TSSs were significantly influenced only by *T*, with an overall mean of 17.9°Bx across all *M* stages. TSS levels generally decreased until Day 10, after which they either stabilized or showed a slight increase by Day 20 (Table 2 and Figure 5). The results of this study are consistent with those reported by other researchers [7, 11] and fall within the range preferred by consumers [6]. TSS values in yellow pitahaya are typically higher than those in red pitahaya, which range between 10°Bx and 14°Bx [27, 39].

TA and MI followed similar trends to TSS. Neither TA nor MI was significantly affected by the *M* stage, except on Day 10 when ripe fruits exhibited the highest acidity value of 0.09 g citric acid/100 g. In contrast, ripe fruits had the lowest MI value of 197.6 at the same time (Figure 5). TA remained relatively constant at approximately 0.1%, while MI ranged from 194.4 to 208.7. Both parameters were significantly influenced by *T*: TA decreased over time from 0.107

TABLE 1: Changes in epicarp color (mean ± standard deviation; $n = 5$) during the storage time (T) of yellow pitahaya fruits collected at different maturity (M) stages. Different lowercase letters indicate significant differences (LSD test, $p < 0.05$) among storage times for each M; different capital letters indicate significant differences (LSD test, $p < 0.05$) among maturity stages for each T.

Colour coordinate	Storage time (days)	Maturity stage Green	 Semiripe	 Ripe
$L*$	1	43.2d ± 4.4 C	49.5d ± 2.3 B	60.7 ± 5.0 A
	5	48.3c ± 5.5 C	54.2c ± 2.3 B	62.6 ± 3.9 A
	10	56.9b ± 4.0 B	59.5b ± 1.8 B	64.8 ± 1.9 A
	15	61.6ab ± 2.6 AB	60.7ab ± 2.0 B	64.5 ± 1.7 A
	20	64.0a ± 0.8	62.6a ± 1.6	62.1 ± 3.9
$a*$	1	−6.4c ± 1.0 B	−3.6e ± 0.4 B	5.8c ± 3.5 A
	5	−6.1c ± 2.1 C	−0.7d ± 1.3 B	7.4bc ± 2.9 A
	10	0.3b ± 3.9 B	5.6c ± 0.2 A	8.9bc ± 2.1 A
	15	5.6a ± 2.8 B	7.7b ± 0.7 AB	10.3ab ± 1.9 A
	20	8.5a ± 2.1 B	9.5a ± 0.5 B	12.2a ± 1.5 A
$b*$	1	16.1c ± 5.7 C	24.5c ± 3.3 B	40.7 ± 3.6 A
	5	23.4b ± 6.3 C	30.4b ± 3.0 B	41.7 ± 3.2 A
	10	38.5a ± 5.1	40.5a ± 2.7	44.1 ± 2.2
	15	43.8a ± 2.4	44.0a ± 2.4	44.0 ± 2.0
	20	42.6a ± 1.3	42.7a ± 2.5	39.9 ± 5.1
ΔE	1	56.8 cd ± 1.7 AB	55.2 cd ± 1.7 C	58.9 ± 1.6 A
	5	56.4d ± 1.6 B	55.1c ± 0.6 B	58.7 ±1.7 A
	10	59.7ab ± 1.3	59.2b ± 1.4	59.6 ± 2.2
	15	60.9a ± 1.3	61.4a ± 1.5	59.7 ± 2.3
	20	58.6bc ± 1.1	59.4b ± 1.7	57.6 ± 2.5

to 0.075 g citric acid/100 g, while MI increased from 171.8 to 240.7 (Table 2). These findings align with previous studies on yellow pitahaya by Sotomayor et al. [11] and on red pitahaya by Velásquez-Cedeño et al. [27]. However, Morillo-Coronado et al. [6] reported higher TA values (0.20%) and lower MI values (87), which may be attributed to differences in experimental conditions or fruit handling practices.

The variation in pH, TSS, TA, and MI due to T, and to a lesser extent M stage, can be attributed to various biochemical processes that occur during storage. These include metabolic and enzymatic activities, changes in sugar concentration, water loss, and external factors such as temperature and relative humidity. Together, these factors influence the chemical composition of yellow pitahaya fruits over time [6, 9, 15].

3.3. Chemical Composition of Fruit Powder. Table 3 presents the chemical composition of yellow pitahaya powder derived from fruits stored for 1 day and harvested at three different M stages. Significant differences were observed for all chemical attributes (ANOVA not shown). Powders obtained from more mature fruits had higher moisture content, while those from green fruits exhibited the highest crude protein, lipid, and ash contents. In contrast, the powder from ripe fruits had the lowest crude fiber content and the highest carbohydrate content. These findings are consistent with those reported by Morais et al. [38], who evaluated the moisture, crude protein, lipids, ash, crude fiber, and carbohydrate contents of *S. megalanthus* and *Hylocereus costaricensis*, obtaining values similar to those observed in this study.

On the other hand, Tomas et al. [13] reported lower values of protein and fat in ripe fruits of *Selenicereus setaceus*, another pitahaya species, which could be attributed to differences in fruit M or species-related variations. Similarly, studies evaluating protein and lipid contents in three varieties of red pitahaya have reported significantly lower values, particularly for protein, with levels up to four times lower than those found in this research [5, 40]. Pitahaya is also recognized as a rich source of dietary fiber, with its peel containing up to 3% of the total available fiber [41]. The fiber content reported in this study is higher than that observed by Tomas et al. [13] in ripe fruits of *S. setaceus*, but comparable to that found in red pitahaya. The similarity in fiber content across studies could be influenced by factors such as cultivation practices and environmental conditions, particularly soil type and climate during fruit ripening [40, 42].

The variations in chemical composition at different M stages can be explained by physiological and biochemical processes. For instance, the higher protein content in green fruits can be attributed to active cellular growth, as these fruits are still undergoing intense metabolic activity. However, protein tends to degrade during the ripening process [8]. Similarly, the observed decreases in lipid, ash, and fiber contents during maturation are likely the result of lipolysis;

TABLE 2: Mean values (± standard deviation) for the three maturity stages ($n = 25$) and the five storage times ($n = 15$) and results of LSD test for all the parameters performed on yellow pitahaya fruits.

	Maturity stage			Storage time (days)				
	Green	Semiripe	Ripe	1	5	10	15	20
Length (mm)	91.4b ± 7.5	96.0a ± 2.8	91.7b ± 3.7	95.8a ± 4.9	94.3ab ± 5.1	93.0abc ± 5.3	91.6bc ± 5.4	90.3c ± 5.7
Diameter (mm)	65.4b ± 4.5	72.0a ± 4.8	71.7a ± 4.8	71.9 ± 5.6	70.8 ± 5.3	69.9 ± 5.4	68.6 ± 5.5	67.3 ± 5.5
Weight loss (%)	8.4a ± 6.9	6.8b ± 5.5	6.5b ± 5.0	0.0e ± 0.0	2.5d ± 0.6	7.3c ± 1.7	11.3b ± 2.4	15.0a ± 2.9
Volume (cm^3)	245.0b ± 37.5	286.8a ± 46.0	278.6a ± 31.7	297.1a ± 46.7	289.7ab ± 49.1	264.8bc ± 30.2	255.5c ± 29.3	243.4c ± 30.5
Firmness (N)	10.9a ± 1.0	10.2b ± 1.1	9.6b ± 0.9	10.6 ± 1.5	10.2 ± 0.8	10.3 ± 0.9	10.1 ± 1.1	9.9 ± 1.1
Moisture (g/100 g)	79.1a ± 3.5	76.4ab ± 3.9	77.3c ± 3.4	77.7 ± 1.9	76.1 ± 5.1	77.9 ± 2.9	79.0 ± 2.6	77.4 ± 4.9
Epicarp %	42.4a ± 7.4	40.6a ± 8.3	26.6b ± 5.3	44.6a ± 9.9	40.0b ± 9.4	36.3c ± 9.9	31.8d ± 7.7	30.0d ± 6.0
Mesocarp + endocarp %	57.6b ± 7.4	59.4b ± 8.3	73.4a ± 5.3	55.4d ± 9.9	60.0c ± 9.4	63.7b ± 9.9	68.2a ± 7.7	70.0a ± 6.0
Epicarp thickness (mm)	2.7a ± 0.6	2.8a ± 0.6	1.9b ± 0.3	3.0a ± 0.8	2.7a ± 0.5	2.3b ± 0.6	2.4b ± 0.5	2.0c ± 0.4
Mesocarp + endocarp thickness (mm)	60.2b ± 5.2	65.8a ± 4.4	68.6a ± 5.3	64.1 ± 6.2	64.3 ± 5.7	64.1 ± 7.3	65.0 ± 5.4	66.5 ± 5.9
$L*$	54.8c ± 8.8	57.3b ± 5.2	62.9a ± 3.6	51.2d ± 8.4	55.0c ± 7.2	60.4b ± 4.3	62.3ab ± 2.6	62.9a ± 2.4
$a*$	0.4c ± 6.6	3.7b ± 5.2	8.9a ± 3.2	−1.4e ± 5.7	0.2d ± 6.1	4.9c ± 4.4	7.9b ± 2.7	10.1a ± 2.1
$b*$	32.9c ± 12.1	36.4b ± 8.2	42.1a ± 3.6	27.1d ± 11.3	31.8c ± 8.8	41.0b ± 4.1	43.9a ± 2.1	41.7ab ± 3.4
ΔE	58.5 ± 2.2	58.1 ± 2.9	58.9 ± 2.1	56.9c ± 2.2	56.7c ± 2.0	59.5b ± 1.6	60.7a ± 1.8	58.5ab ± 1.9
pH	4.6b ± 0.3	4.5b ± 0.3	4.7a ± 0.2	4.3e ± 0.1	4.4d ± 0.2	4.6c ± 0.1	4.7b ± 0.1	4.9a ± 0.1
Soluble solids (°Brix)	17.8 ± 0.8	17.8 ± 0.8	18.1 ± 0.8	18.3a ± 0.5	18.3a ± 0.9	17.5b ± 0.8	17.4b ± 0.7	17.9ab ± 0.8
Acidity (g citric acid/100 g)	0.089 ± 0.021	0.094 ± 0.017	0.089 ± 0.016	0.107a ± 0.009	0.108a ± 0.017	0.081bc ± 0.012	0.084b ± 0.011	0.075c ± 0.006
Maturity index	207.3 ± 40.0	194.4 ± 35.1	208.7 ± 36.6	171.8c ± 15.5	173.8c ± 28.0	219.7b ± 31.1	211.4b ± 31.6	240.7a ± 22.8

Note: Different lowercase letters indicate significant differences (LSD test, $p < 0.05$) among maturity stages or storage times.

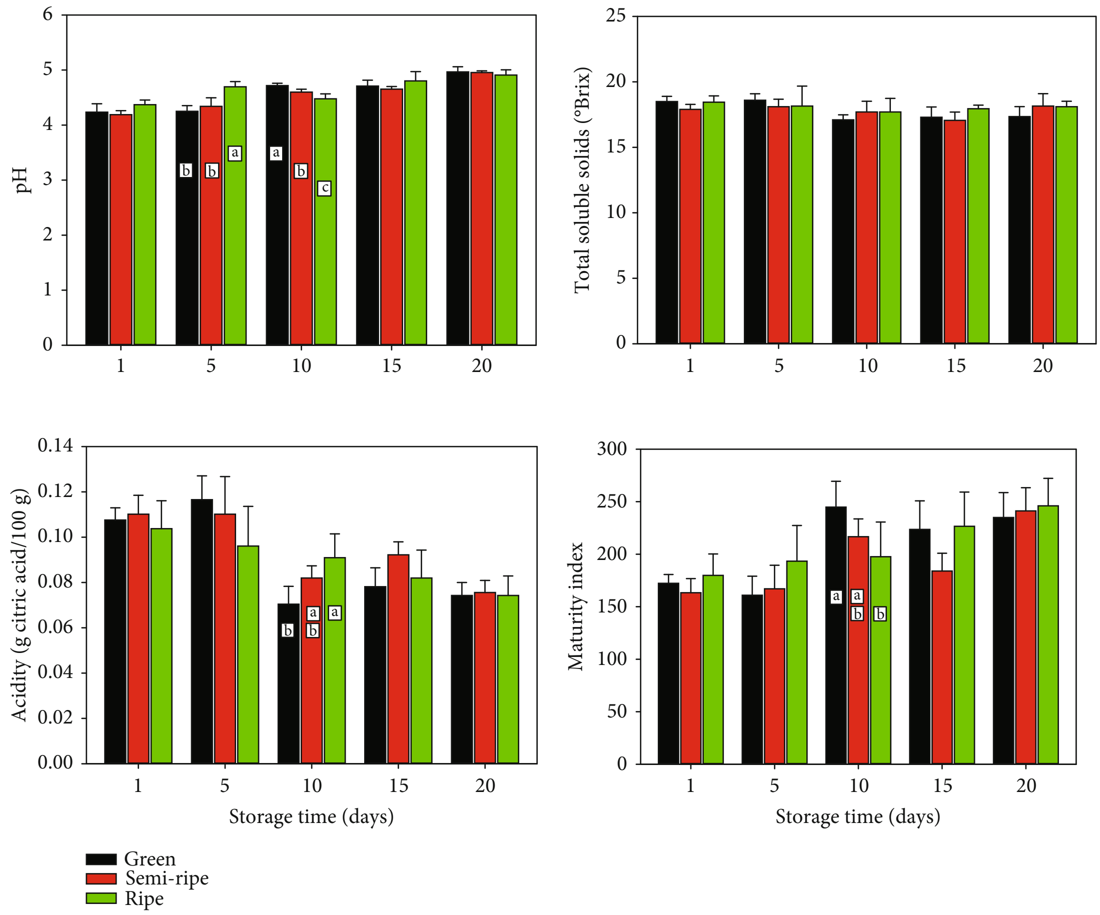

FIGURE 5: pH, total soluble solids, titratable acidity, and maturity index of yellow pitahaya fruits (*Hylocereus megalanthus*) collected at three maturity stages during 20 days of storage. Bars represent standard deviation ($n = 5$). Different letters on each evaluation day indicate statistically significant differences according to the Tukey test ($p < 0.05$), for each maturity stage (MS).

TABLE 3: Chemical composition and bioactive properties (mean ± standard deviation; $n = 3$) of yellow pitahaya powder obtained from 1-day fruits collected at different maturity stages.

	Green	Semiripe	Ripe
Moisture (g/100 g DM)	8.02c ± 0.65	9.98b ± 0.51	11.30a ± 0.69
Protein (g/100 g DM)	6.16a ± 0.06	5.31b ± 0.18	4.18c ± 0.21
Lipid (g/100 g DM)	3.08a ± 0.05	2.78b ± 0.02	2.32c ± 0.11
Ash (g/100 g DM)	2.21a ± 0.04	2.02b ± 0.01	1.84c ± 0.08
Fiber (g/100 g DM)	6.20a ± 1.14	6.70a ± 0.30	3.83b ± 0.47
Carbohydrate (g/100 g DM)	74.32b ± 1.60	73.22b ± 0.77	76.54a ± 0.19
Total phenols (mg GAE/g DM)	2.51c ± 0.05	2.67b ± 0.10	3.35a ± 0.05
Antioxidant capacity (mg TE/g DM)	1.73a ± 0.01	1.75a ± 0.01	1.69b ± 0.01

Note: Different lowercase letters indicate significant differences (LSD test, $p < 0.05$) among maturity stages.
Abbreviations: DM, dry matter; GAE, gallic acid equivalent; TE, Trolox equivalent.

other metabolic processes; and changes in the concentrations of cellulose, hemicellulose, and pectin [13].

3.4. Bioactive Properties of Fruit Powder. The bioactive properties of the fruit powder, including TPC and antioxidant capacity, are presented in Table 3. Significant differences were observed for all parameters (ANOVA not shown). Ripe fruits exhibited the highest TPC (3.35 mg GAE/g) but had the lowest antioxidant capacity (1.69 mg TE/g). This inverse relationship could be attributed to the increase in TSS, carbohydrates, and oxidative stress that occur during maturation and senescence, which can reduce the availability of phenolic compounds and, consequently, affect the fruit's antioxidant capacity [43, 44]. These trends align with the findings of Hua et al. [17], who studied three pitahaya varieties. The TPC in red-fleshed pitahaya followed a quadratic pattern during development, increasing from 28 to 36 days after anthesis, then decreasing at 42 days after anthesis [45].

The antioxidant capacities reported in Table 3 are consistent with values obtained by Al-Mekhlafi et al. [1], who measured capacities between 1.9 and 2.02 mg TE/g in yellow pitahaya fruits at optimal *M*. However, Paśko et al. [46] reported higher antioxidant capacities in both red (3.5–5.5 mg TE/g) and yellow (2.1 mg TE/g) pitahaya. This difference could be attributed to the presence of betacyanins in red pitahaya, which contribute to greater antioxidant potential, compared to the lower levels of betaxanthins found in yellow pitahaya fruits [47, 48].

Understanding the variations in bioactive compounds in yellow pitahaya based on *M* stage provides valuable insights into the fruit's biology. This knowledge has practical implications for the food industry and human health, and it can aid in optimizing harvesting, production, and marketing strategies. Additionally, it is relevant for advancing scientific research on bioactive compounds [1, 9, 10, 13, 15].

4. Conclusions

The *M* stage significantly influenced the chemical composition, bioactive properties, and most physicochemical characteristics of yellow pitahaya, with the exception of firmness and TSSs. *T* also affected these characteristics, excluding diameter, firmness, and mesocarp plus endocarp thickness. The interaction between *M* and *T* significantly impacted weight loss, color parameters, acidity, and MI.

Ripe fruits showed higher percentages of mesocarp + endocarp, color parameters, pH, moisture, carbohydrates, and TPC, while green fruits exhibited higher weight loss, epicarp percentage, epicarp thickness, proteins, lipids, and ashes. Storage led to significant reduction in length, volume, epicarp percentage, epicarp thickness, soluble solids, and acidity, while weight loss, mesocarp + endocarp percentage, color parameters, pH, and MI increased over.

This study identified optimal values for key variables at later *M* stages, recommending semiripe and ripe stages for harvesting yellow pitahaya. Ripe fruits are ideal for nearby markets, as they allow for quick transportation with minimal quality loss, while semiripe fruits are more suitable for distant markets due to their longer shelf life.

These findings offer valuable insights for improving harvest strategies and market distribution, ultimately enhancing the quality and availability of yellow pitahaya.

4.1. Limitations and Future Research Directions. While this study has provided valuable insights into the physicochemical, biochemical, and bioactive characteristics of yellow pitahaya at different *M* stages and *T*s, several limitations exist. One limitation is the focus on a single variety grown under specific environmental conditions, which may limit the generalizability of the findings. Future research should explore the impact of different growing regions, climate conditions, and postharvest treatments on fruit quality. Additionally, further investigation into the mechanisms driving the observed biochemical changes during storage would be beneficial. Expanding the scope to include a comprehensive analysis of bioactive compounds and their potential health benefits at different maturation stages could significantly contribute to the field. These studies would help optimize harvesting and storage protocols for commercial applications.

Data Availability Statement

The data supporting the findings of this study will be made available upon request from the journal's editors or authorized representatives.

Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. *(Supporting Information)* Table S1: Results of the two-way analysis of variance (mean square and significance) for the physicochemical characteristics evaluated in yellow pitahaya fruits.

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