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Wild passion fruit flour quality: Effect of cultivation system and harvest time

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Abstract:
The wild passion fruit (*Passiflora cincinnata* Mast.) is an edible fruit with a great agro-industrial potential. Its peel is highly nutritious; however, it is often discarded as waste.
This study aimed to produce and evaluate the physicochemical and nutritional properties of flour made from the peel of wild passion fruit "Cerro Corá". The fruit was grown under both irrigated and rainfed conditions and harvested at different times. The completely randomized factorial design (2×3) comprised two cultivation systems (irrigated and rainfed) and three harvest times (60, 80, and 100 days after anthesis).
The moisture content and water activity of the flours did not depend on the cultivation system. The greatest preservation of phenolic compounds was observed in the samples grown under rainfed conditions. The best physicochemical profile and bioactive content belonged to the flour samples produced 80 days after anthesis. These flours can be used as ingredients for functional food products due to their antioxidant potential.

Keywords: *Passiflora cincinnata* Mast., convective drying, waste utilization, fruit by-products, nutritional value, physicochemical properties

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INTRODUCTION

The passion fruit processing industry generates a large amount of waste, primarily peels, which are often underutilized despite their high nutritional content and bioactive compounds. One of the solutions to reduce waste and enhance its value is to process passion fruit peels into flour for various food and health applications. However, such environmental factors as cultivation systems and harvest time may affect the quality of the resulting flour. In this study, we assessed the effects of cultivation systems (rainfed and irrigated) and harvest time on the physicochemical and bioactive profile of wild passion fruit (*Passiflora cincinnata* Mast.) to determine the optimal conditions for producing high-quality flour.

Passion fruit production is important for the Brazilian economy: it requires intensive labor and generates reliable income, allowing for continuous fruit harvest throughout the year [1]. The passion fruit belongs to the *Passifloraceae* family and includes various species. *P. cincinnata* is commonly known as the wild passion fruit, or *maracujá-da-Caatinga* [2]. This wild species is resistant to drought and various pests and diseases. The plant is adaptable to adverse conditions, with potential for both rainfed and irrigated cultivation areas, which contributes to increased fruit productivity. The harvest season is a crucial factor that can directly affect the constituents of wild passion fruit. Consequently, the quality of the fruits during the post-harvest period depends on the harvest time and the ripeness stage [2, 3].

Wild passion fruit has a sweet, exotic flavor and high nutritional value. As a result, it is well-received by the consumer market. It holds significant socioeconomic importance for populations in the semi-arid regions who harvest the fruits for commercial sale [4]. *P. cincinnata*

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fruits can be consumed fresh or used as raw material in the food, chemical, or pharmaceutical industries [5].

Fruit processing generates by-products, primarily peels and seeds, which rarely find an adequate destination [6]. According to the data on passion fruit production, the current processing technique generates approximately 50% of the total fruit weight as waste, most of which is peel. Consequently, obtaining industrial products from the proper processing of passion fruit waste helps optimize the economics of processing units [7, 8].

Some recent studies have explored different approaches to utilizing passion fruit peel waste, including its incorporation into functional foods and dietary supplements. However, many of these studies focus on chemical composition rather than practical processing methods [9, 10]. Additionally, most authors fail to assess the combined effects of environmental conditions, harvest time, and drying methods on the final quality of flour. Addressing these gaps, we evaluated the impact of cultivation systems (irrigated vs. rainfed) and harvest time on the physicochemical and nutritional properties of *P. cincinnata* peel flour.

Refined drying techniques can enhance the quality of passion fruit peel flour, which makes them a promising approach in flour processing. For instance, a controlled drying process improves the flour consistency, nutritional content, and bioavailability of beneficial compounds. Although it remains understudied, this technique can enhance the functional properties of the flour, making it more suitable for food applications.

Passion fruits are rich in peel, which consists of flavedo (outer skin) and albedo (white inner part). These parts offer various health benefits, e. g., reducing such biochemical parameters as glucose, total cholesterol, and triglycerides [9, 10]. These properties, combined with the high nutritional value, make utilizing passion fruit peel a source of health benefits for human consumption. This viable alternative reduces costs and mitigates issues associated with waste disposal from processing [11]. The by-products of passion fruit production can be utilized by cooking the albedo or turning it into flour [12].

The peel of *P. cincinnata* contains a diverse composition of bioactive compounds and essential nutrients, making it a valuable ingredient for food applications. It is rich in soluble sugars, phenolic compounds, flavonoids, anthocyanins, ascorbic acid, and carotenoids. These compounds provide antioxidant, metabolic, and physiological benefits, supporting the application of wild passion fruit peel in the functional food industry. The nutritional and bioactive properties of *P. cincinnata* peel flour position it as a sustainable and valuable alternative for food fortification, waste reduction, and industrial applications.

To minimize environmental impacts and provide a new source of income, one viable alternative is employing fruit peel drying. This technique reduces the moisture content in food, thus preserving its physical and chemical characteristics, which makes the food safer and extends its shelf-life [13]. Such environmental factors as irrigated vs. rainfed cultivation systems and harvest time affect such parameters of flour quality as fiber content, bioactive compounds, and antioxidant capacity. While some studies have addressed these factors separately, very few publications provide a comprehensively analysis of their combined effects on flour quality. Understanding how these variables impact the nutritional and functional properties of the flour may yield more tailored processing methods to optimize the final product quality.

Given this, we aimed to enhance the nutritional value of the processed product, reduce economic losses, and mitigate negative environmental impacts from waste disposal [14]. We evaluated the quality of flour samples made from the peel of wild passion fruit *P. cincinnata* (Cerro Corá) grown under both rainfed or irrigated conditions and harvested at different times. The findings offer practical applications by proposing more efficient utilization of industrial waste, reducing disposal-related environmental impacts, and demonstrating strategies to improve the nutritional value of passion fruit peel flour. These solutions can enhance its potential for functional foods, contributing to the development of sustainable and value-added products.

STUDY OBJECTS AND METHODS

Experimental design. The research had a completely randomized design with the following factorial scheme: 2 (cultivation systems: rainfed vs. irrigated)×3 (fruit harvest times: 60, 80, and 100 days after anthesis). All experiments were conducted in four replicates.

Producing flour from *Passiflora cincinnata* Mast. peel. The fruits were harvested from plants in rainfed and irrigated cultivation systems. Marked with tape and permanent marker on the day of pollination, they were monitored until harvest. When they reached the predetermined harvest time (60, 80, and 100 days after anthesis), they were manually harvested, placed in polyethylene trays, and transported by vehicle to the laboratory for visual inspection to ensure absence of peel injuries. The task was to select uniform and high-quality samples.

The fruit peel was separated from the pulp and seeds through manual pulping. Subsequently, the peel was cut into small cubes of approximately 1.5×1.5×1.5 cm. After cutting, the peel was spread on a tray with a 50-mesh screen 20×20 cm (2.0×3.5 mm mesh size). The material was dried in an air-circulating oven at 75°C to a constant weight, then removed from the trays and blended in a household blender (Mondial Power Red L77) for approximately 45 s. After being sieved through a stainless-steel sieve to obtain a finer flour with greater product homogeneity, it was finally stored in containers for subsequent analysis (Fig. 1).

Physical and physicochemical analyses of the fruit peel flour. The yield, %, was calculated using the initial mass of the raw material and the final mass after product preparation [15].

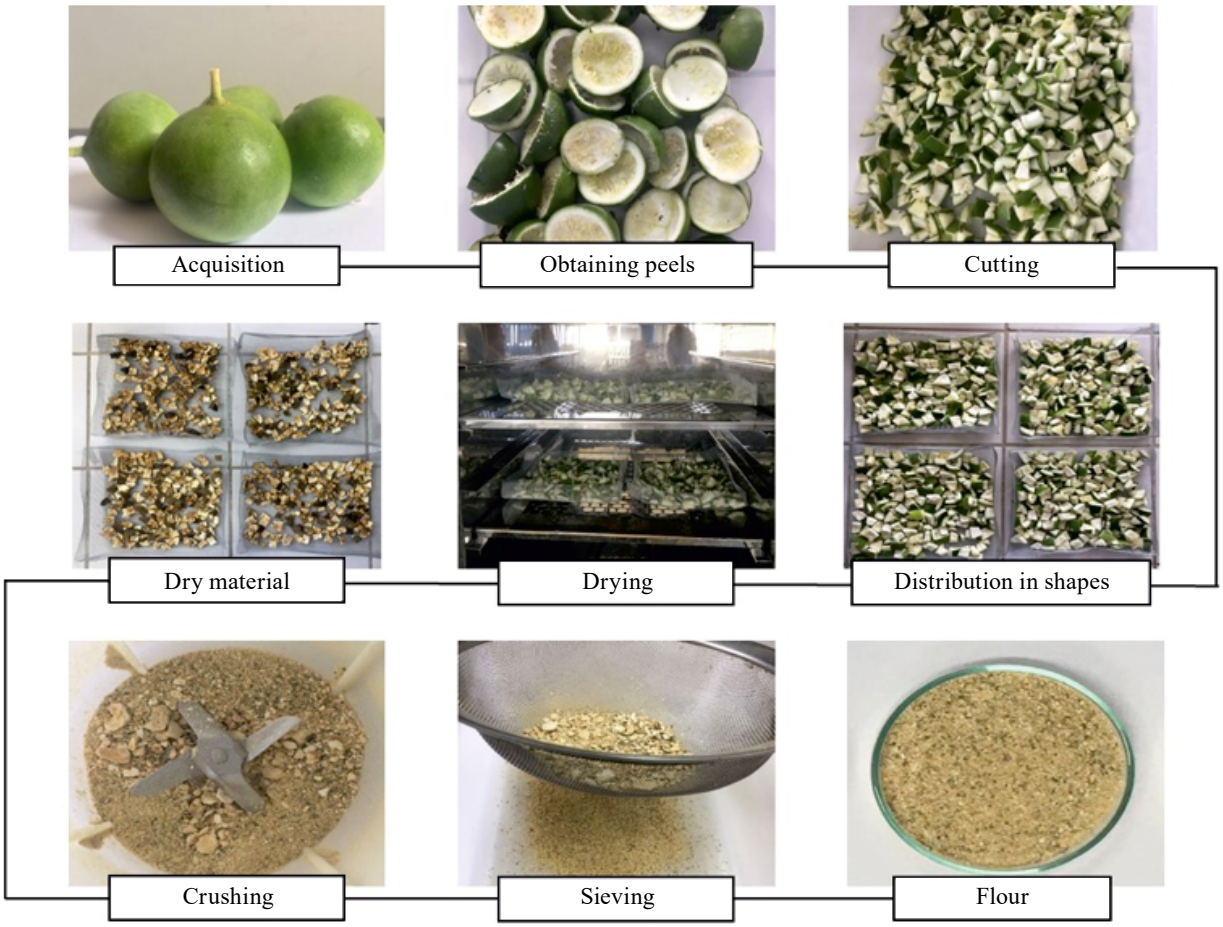


Figure 1 *Passiflora cincinnata* Mast. fruit peel flour: Production stages

The bulk density, g/cm^3, was the ratio of the sample mass to the volume occupied by its solid particles. 5 g of the sample were weighed and transferred to a 5 mL graduated cylinder, observing the displacement [16].

To determine the solubility, %, we weighed 0.1 g of the sample and added 10 mL of distilled water. The mix was then centrifuged at 3,000 rpm for 5 min. Next, 2 mL of the supernatant was transferred to a Petri dish and placed in an oven at 105°C for 1 h, followed by cooling in a desiccator for 30 min. The material was then reweighed to obtain the solubility values.

The water activity determination involved an AquaLab instrument (Decagon Devices, 3T). A sufficient amount of flour to cover the bottom of the capsule was placed with a spatula directly in the equipment at 25°C for readings. The water activity was expressed as free water.

To define the moisture content, %, we dried pretared crucibles in a Solab oven (model SL-101) at 105°C for 13 h. After cooling them in a desiccator to room temperature, we reweighed them by the method outlined by the Adolfo Lutz Institute [17].

The colorimetric analysis relied on the CIELAB system with a colorimeter (Konica Minolta, CR 300), determining luminosity (L^*), chromaticity coordinates a^* and b^*, and chroma (C^*) [18].

We determined the titratable acidity, %, by homogenizing 0.25 g of flour in 50 mL of distilled water, followed by titration against 0.1 M sodium hydroxide solution until the endpoint indicated by phenolphthalein. The result was expressed as a percentage of citric acid [17].

The pH level was analyzed by direct reading in an extract prepared with 1.0 g of flour and 10 mL of distilled water, using a benchtop digital pH meter (Digimed, DM-22).

To define the concentration of H^+ ions, µM, we converted the pH values using the equation $[H^+] = 10^{-pH}$.

The analysis of soluble solids, %, involved an extract prepared with 1 g of flour and 10 mL of distilled water, as well as a digital refractometer with automatic temperature compensation (Brand, Digital Refractometer).

To obtain the soluble solids/titratable acidity (SS/TA) ratio, we divided the soluble solids values by the titratable acidity values.

The content of soluble sugars, g/100 g, was determined using the Anthrone method [19]. We prepared an extract by diluting 0.1 g of flour in 50 mL of distilled water. A solution containing 0.05 mL of extract, 0.95 mL distilled water, and 2.0 mL the Anthrone solution (0.2%) was prepared in tubes placed in an ice bath. The tubes were quickly shaken using a shaker (Biomixer, QL-901) and then placed in a thermostatic bath (Fisatom, 550) at 100°C for 3 min. The content of soluble

sugars was determined by spectrophotometry (Spectrum) at 620 nm, using glucose as a reference to obtain the standard curve.

To find out the content of reducing sugars, g/100 g, we applied the dinitrosalicylic acid method [20]. First, we prepared an extract by diluting 0.1 g of flour in 50 mL of distilled water. Then, we mixed a solution containing 0.4 mL of extract, 0.1 mL distilled water, and 0.5 mL dinitrosalicylic acid solution. The tubes were quickly shaken in a shaker (Biomixer, QL-901) and then placed in a thermostatic bath (Fisatom, 550) at 100°C for 5 min. The content of reducing sugars was determined by spectrophotometry (Spectrum) at 540 nm, using glucose as a reference to obtain the standard curve.

We defined the amount of non-reducing sugars, g/100 g, by subtracting the reducing sugars content from the soluble sugars content.

Analysis of bioactive compounds. The content of ascorbic acid, mg/100 g, was determined following the standards established by the Adolfo Lutz Institute [17]. We weighed 0.10 g of the sample to transfer it to Erlenmeyer flasks along with 50 mL of chilled 0.5% oxalic acid. They were then titrated against the Tillman's solution until the endpoint.

For total chlorophyll and carotenoids, mg/100 g, we macerated 0.25 g of flour with a mortar and pestle in 0.2 g of calcium carbonate and 5 mL of chilled acetone (80%). After centrifuging (Cientec) the samples at 3,000 rpm for 10 min at 10°C, we determined the content of total chlorophyll and total carotenoids in the supernatant by spectrophotometry at 470, 646, and 663 nm [21].

The total phenolic analysis relied on the Folin-Ciocalteu method [22]. First, we prepared an extract by diluting 0.1 g of flour in 50 mL of distilled water. Then, we prepared a solution containing 500 µL of extract, 1,625 µL distilled water, and 125 µL Folin-Ciocalteu's reagent in tubes. The tubes were quickly shaken using a shaker (Biomixer, QL-901) and left to stand at room temperature for 5 min. After adding 250 µL sodium carbonate solution (20%), the tubes were shaken again and placed in a water bath (Hemoquímica) at 40°C for 30 min. The content of total phenolic compounds, mg/100 g, was determined by spectrophotometry (Spectrum) at 765 nm, using gallic acid as a reference to obtain the standard curve.

To find out the content of flavonoids and anthocyanins, we macerated 0.25 g of flour with mortar and pestle in 5 mL of ethanol-HCl (1.5 M) and placed it in a refrigerator at 6°C for 24 h. After centrifuging the samples at 10°C and 3,000 rpm for 10 min in a refrigerated centrifuge (CT-500R), a portion of the supernatant was transferred to cuvettes and read on a spectrophotometer (Spectrum, SP). The content of flavonoids and anthocyanins, mg/100 g, was determined by spectrophotometry at 374 and 535 nm, respectively [23].

Statistical analysis. The data obtained were subjected to the analysis of variance and the Tukey's test. The data processing also involved a principal component analysis with clustering. The Statistical Software R [24] was used for the statistical analyses.

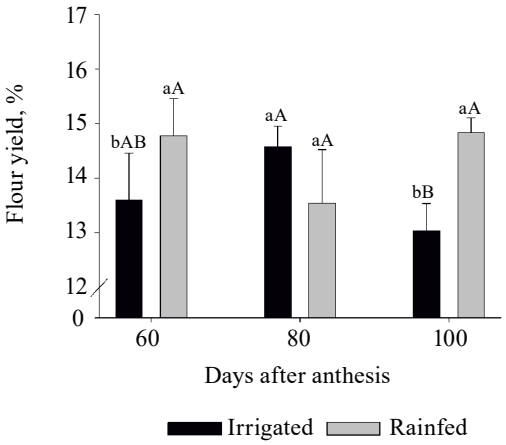
RESULTS AND DISCUSSION

Physical and physicochemical properties. The yield of *Passiflora cincinnata* Mast. peel flour depended on the cultivation system and harvest time. The flours obtained from rainfed cultivation showed superior results compared to irrigated cultivation at 60 days (8%) and 100 days (12%) after anthesis, with both being equal only at 80 days after anthesis (Fig. 2).

When considering the rainfed treatment alone, no statistical difference was found in the yields obtained for the different harvest times. Lima *et al.* [25], who analyzed *P. cincinnata* peel flour, obtained a yield of 19.5%, which exceeded our results. Such differences could be attributed to variations in flour extraction methods because values are not standardized across all passion fruit flours due to variations in peel composition and drying methods [25, 26].

The increased yield of the flour samples obtained from the peels of fruits grown under rainfed conditions at 60 and 100 days after anthesis may be attributed to a lower water content and a higher dry matter content in their peels compared to the fruits grown with irrigation. This information is consistent with Rybka *et al*. [27], who emphasize that yield values may be specifically correlated with the amount of water present in the peel composition of this fruit. The values found for density, solubility, and moisture content of the peel flours showed no statistical differences between cultivation systems and harvest times (Table 1).

The values obtained for density ranged from 0.91 to 1.08 g/cm for the two factors studied (Table 1). These values were relatively high, indicating that the low number of void spaces between the particles of the flour made it denser. The apparent density assists in specifying packaging, transportation, and storage requirements. It depends on particle size, properties, and material composition [28].



Cultivation systems followed by the same lowercase letter and harvest time followed by the same uppercase letter did not differ from each other by Tukey's test at a 5% probability level

Figure 2 Flour yield from *Passiflora cincinnata* Mast. fruit peel

Table 1 Physical and physicochemical variables of *Passiflora cincinnata* Mast. fruit peel flours under study

Harvest time, days after anthesis	Cultivation system					
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
	Density, g/cm		Solubility, %		Moisture, %	
60	1.06	0.91	93.91	93.72	9.25	8.51
80	1.07	1.07	92.71	93.24	9.44	9.32
100	1.08	1.06	93.01	93.64	9.42	9.29

When analyzing the cultivation systems and harvest times, the solubility results ranged from 92.71 to 93.91% (Table 1). These solubility values highlight that the *P. cincinnata* flour exhibited high water solubility, which is crucial for its use in food formulations.

The moisture values for the two factors studied ranged from 8.51 to 9.44% (Table 1). The low moisture content in the flour samples helps prevent microbiological contamination [29]. All the *P. cincinnata* flour samples met the standards required by the current legislation, where the maximal moisture content in flours is 15% [30].

The water activity of the flour samples showed isolated effects across harvest times. The flour from the fruit peel harvested at 60 days after anthesis was 2% higher than at 80 days and 5% higher compared to the samples harvested 100 days after anthesis (Fig. 3a).

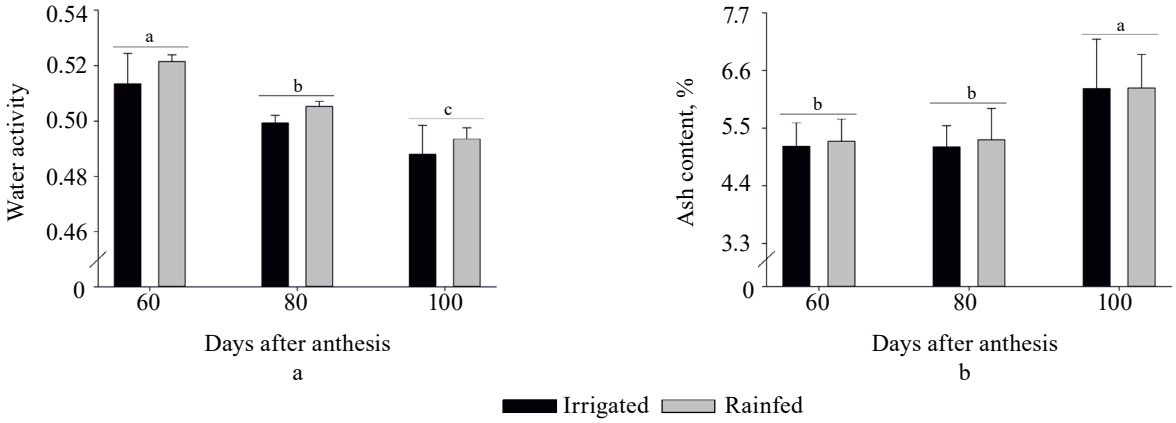
As for water activity, we detected a decrease in values as fruit maturation increased. As the fruit remained on the plant for more days, the water activity in its peel decreased. All water activity values analyzed in the flours were below 0.6, thus considered to exhibit low microbial growth potential [31]. Other authors reported that low moisture content and water activity were critical for the stability and preservation of fruit residue-derived flours [32, 33]. The low water activity not only inhibited the microbial growth but also reduced the enzymatic activity, thereby enhancing the shelf-life.

The ash contents showed isolated effects for harvesting times (Fig. 3b). The flour from fruits harvested at a more mature stage (100 days after anthesis) exhibited a higher ash concentration (6.26%): it differed from the other flours analyzed at 80 and 60 days after anthesis, which showed percentages of 5.20% each. A value similar to those found in this study was observed by Jinkings *et al.* [34], who reported 6.97% when analyzing flour from the exocarp of *Passiflora edulis* Sims.

The ash content reveals the total mineral content in a sample [35]. The fruits harvested 100 days after anthesis resulted in higher ash values, which may indicate a greater accumulation of minerals in the fruits over time. Similar behavior was reported by de Aquino *et al.* [36] for the physicochemical profile of green and ripe neem (*Azadirachta indica* A. Juss) fruits.

Regarding the coloration of *P. cincinnata* fruit peel flours, we observed some differences when analyzing isolated effects. The luminosity test showed isolated effects for both rainfed and irrigated cultivation systems. The luminosity of flours produced from irrigated fruits was 5% higher compared to those from rainfed treatments (Fig. 4a).

The change in luminosity may result from variations in the fruit color before processing, affected by biochemical reactions and physiological changes due to chlorophyll degradation and carotenoid synthesis during ripening [37]. The results obtained here for luminosity stayed below 50, indicating a darker coloration of the flours produced, which is favorable. According to Barros *et al.* [38], consumers regard a darker coloration in food products positively as it is associated with whole, artisanal, and healthier products.



Cultivation systems followed by the same lowercase letter and harvest times followed by the same uppercase letter do not differ from each other by Tukey's test at a 5% probability level

Figure 3 Water activity (a) and ash content (b) of *Passiflora cincinnata* Mast. fruit peel flour

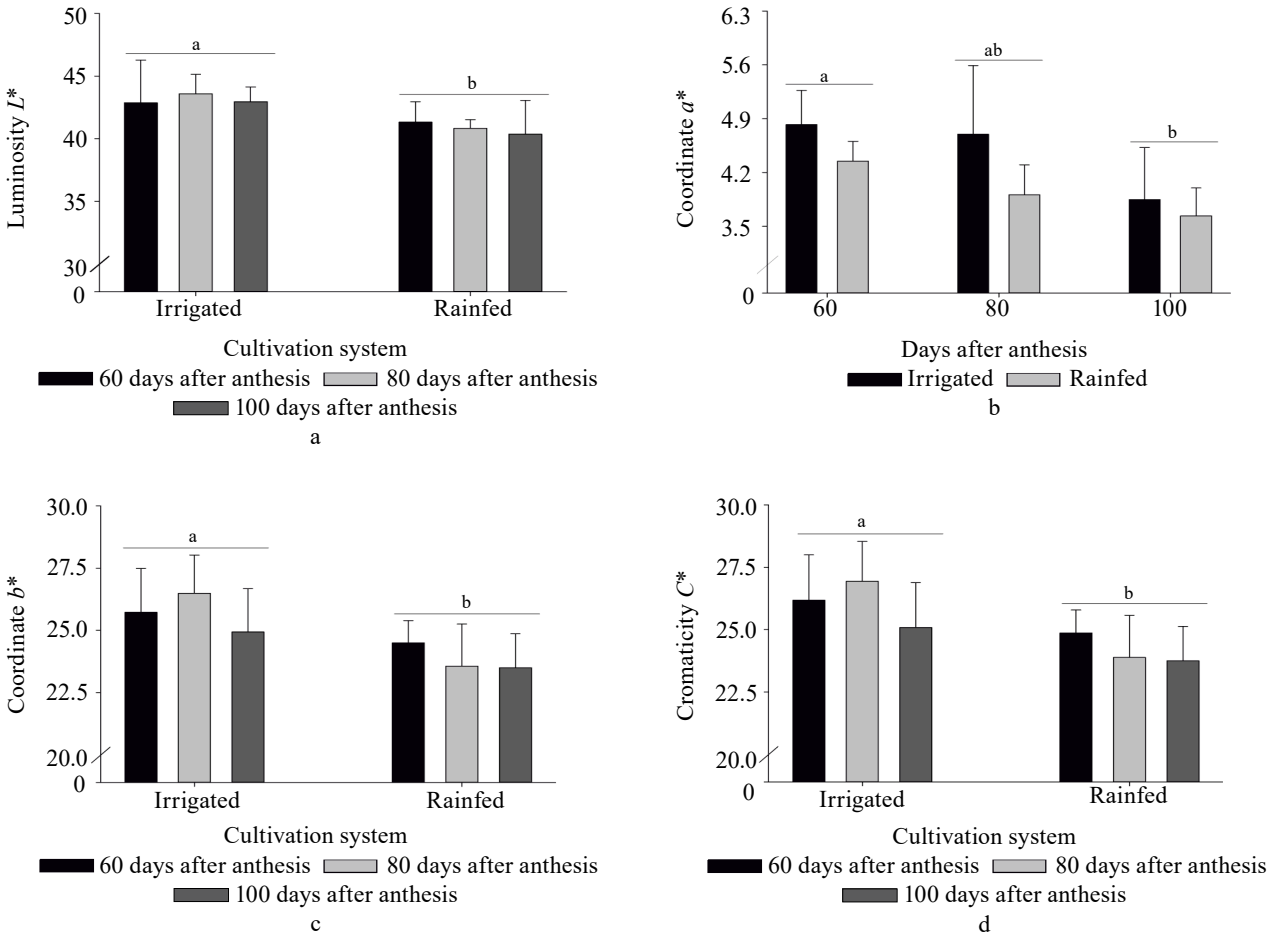


Figure 4 Luminosity *L**(a), coordinate *a** (b), coordinate *b** (c), and chromaticity *C** (d) of *Passiflora cincinnata* Mast. fruit peel flour under study

The values for the coordinate *a** showed isolated effects for different harvest times (Fig. 4b). The values of flours produced at 60 days after anthesis were higher than those obtained at 80 (6%) and 100 (18%) days after anthesis. The coordinate *a** indicates color variations between green (–*a**) and red (+*a**) [39]. Thus, the results obtained demonstrate that the decrease in the value for this coordinate was observed in the flour produced from more mature fruits, indicating a lesser intensification of red color in these flours.

The coordinate *b** observed in the flours depended on the cultivation system (Fig. 4c), with higher values obtained in the flours produced from fruits cultivated with irrigation, which were 7% higher than those from the dryland treatment. Kurek & Sokolova [39] emphasized that positive values for the coordinate *b** indicated a tendency towards yellowish coloration. The color of food products is an important aspect to analyze: not only does it affect the product acceptance but it also corresponds to its quality since the yellowish hue may be related to the presence of carotenoids in the analyzed material [40].

The chromaticity values showed isolated effects for the irrigated and dryland cultivation methods (Fig. 4d). The values for this variable were 7% higher when for the samples obtained by irrigation. The results obtained here stayed below 50, indicating colors with low intensity. Low saturation or chromaticity is desirable for food products as it promotes a more neutral color in the final product. Chromaticity of a product corresponds to its expressiveness, color intensity, and clarity.

Regarding the hue angle, color index, and darkening index, we detected no differences observed between the cultivation methods (irrigated and rainfed) and harvesting times, indicating that these two factors did not affect these variables (Table 2). The hue angle corresponds to color shades [41], where 0° angle represents red, 90° means yellow, 180° stands for green, and 270° is blue. Therefore, the flours produced tended towards yellowish hues because values approaching 90° indicate yellow [42].

The values obtained for the color index were low (< 1), possibly because the flour was produced from *P. cincinnata* peels, which have a green coloration. Brasil & Siddiqui [37] reported a higher amount of chlorophyll in green-colored tissues, which explains these low values found for all the flours produced.

Table 2 Color variables of *Passiflora cincinnata* Mast. fruit peel flours from irrigated vs. rainfed cultivation and harvested at different harvest times

Harvest time, days after anthesis	Cultivation system					
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
	Hue angle, Hº		Color index		Darkening index	
60	79.38	79.95	0.83	0.83	94.47	92.52
80	79.65	80.53	0.79	0.82	96.75	88.57
100	80.59	81.73	0.74	0.77	88.74	90.07

The darkening index of the flours (> 88) was consistent with the values obtained for luminosity, which approached 50, indicating a less translucent product. The darkening index may also be related to the synthesis of carotenoids, which are important pigments known as antioxidants [43].

The titratable acidity depended on the cultivation systems and fruit harvesting times. We detected a decrease in titratable acidity values across the three harvesting times for both cultivation systems used. The observed decrease from the first (60 days after anthesis) to the last harvest (100 days after anthesis) for the flours produced from irrigated fruits was 46%; for the flours obtained from rainfed cultivation, it was 29% (Fig. 5a).

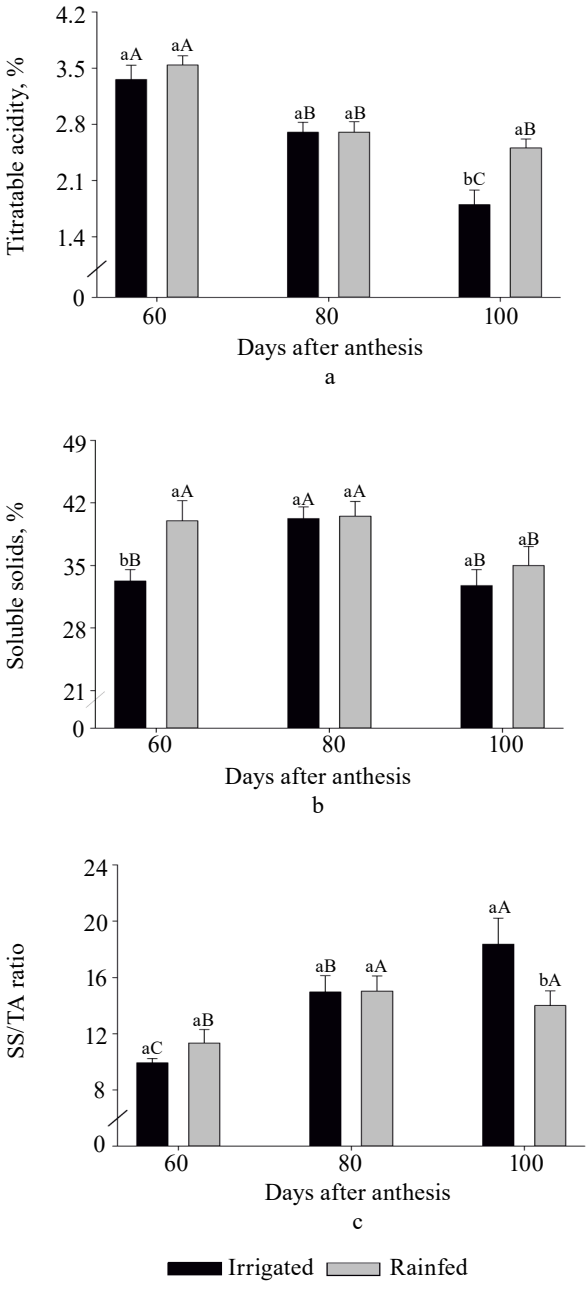
As reported by Rayson *et al.* [44], acidity generally tends to decrease as fruits mature. Garrido *et al.* [45], who analyzed flour made from the peel of *Passiflora edulis* f. flavicarpa Deg, found citric acid levels of 2.35%, i. e., very close to those found in this study. The lower acidity levels in the flours produced from peels of more mature fruits possibly occur because certain organic acids are utilized as substrates during cellular respiration as fruit ripens [46].

The soluble solids content found in the flours exhibited correlations between the factors (Fig. 5b). The flour samples produced from fruits harvested 60 days after anthesis resulted in a higher soluble solids content (16%) compared to those produced at the same time under irrigated cultivation. For other harvest times, we detected no statistically significant difference between cultivation systems. However, both cultivation systems showed a reduction in these contents for the flour samples produced 100 days after anthesis compared to those produced at 80 days, decreasing by 18% for the irrigated treatment and 13% for rainfed cultivation.

The possible increase in the values obtained for the rainfed treatment occurred because this variable was affected by climatic conditions, particularly by rainfall regime or irrigation levels; in this case, the more water the plant receives, the lower the soluble solids content of the fruits [47].

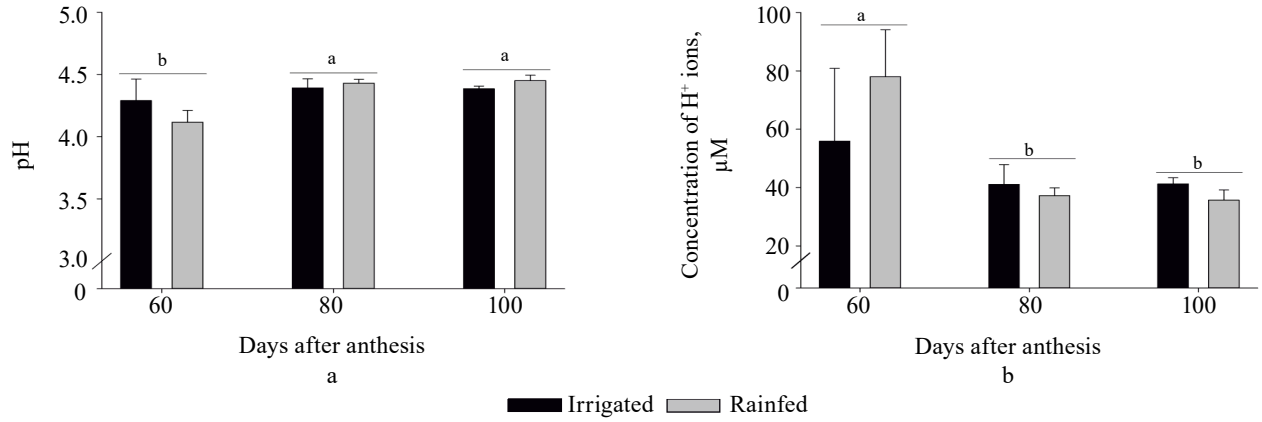
D'Abadia *et al.* [48], who studied the ripening stage and fruit characteristics in two populations of *P. cincinnata*, also observed an increase in soluble solids content 80 days after anthesis. Therefore, the fruit was already in the ripening process, which led to variations and increases in physicochemical compounds, such as soluble solids [49].

The soluble solids/titratable acidity (SS/TA) ratio showed a correlation between the studied factors (Fig. 5c). For the irrigated cultivation system, the flours ex-



Cultivation systems followed by the same lowercase letter and harvest times followed by the same uppercase letter do not differ from each other by Tukey's test at a 5% probability level

Figure 5 Titratable acidity (a), soluble solids (b), and soluble solids/titratable acidity (SS/TA) ratio (c) of *Passiflora cincinnata* Mast. fruit peel flour



Cultivation systems followed by the same lowercase letter and harvest times followed by the same uppercase letter do not differ from each other by Tukey's test at a 5% probability level

Figure 6 pH (a) and concentration of H^+ ions (b) in *Passiflora cincinnata* Mast. fruit peel flour, irrigated vs. rainfed and harvested at different harvest times

hibited an increase in values 100 days after anthesis period, which was higher compared to both the 60-day (45%) and 80-day (18%) periods after anthesis. Conversely, for rainfed cultivation, the highest values were observed at the 80- and 100-day periods, with no statistical difference between them. The values at 60 days were lower (32%) than those found in flours obtained at 80 days after anthesis.

The SS/TA ratio is indicative of flavor, related to the balance of acids and sugars. Therefore, *P. cincinnata* flour exhibits a pleasant taste. The increase in the SS/TA ratio values in the flours obtained at 80 and 100 days after anthesis (rainfed treatment) and at 100 days after anthesis (irrigated treatment) may vary according to the cultivar, location, and harvest time. Primarily, it happened due to the decrease in acidity during fruit ripening, which increases the ratio and enhances palatability [50].

The pH values were individually affected for different harvest times. The statistically equal values observed in the flours produced at 80 and 100 days after anthesis were higher (4%) than the value found in the flour produced at 60 days after anthesis (Fig. 6a).

The increase in pH values in flours produced from more mature fruit peels was consistent with the acidity levels found: higher pH values indicate lower acidity in the product. This behavior was expected, as fruit acidity tends to decrease as they ripen. The pH determination provides valuable data for assessing food preservation status, enabling a better microbiological control in flour processing [51].

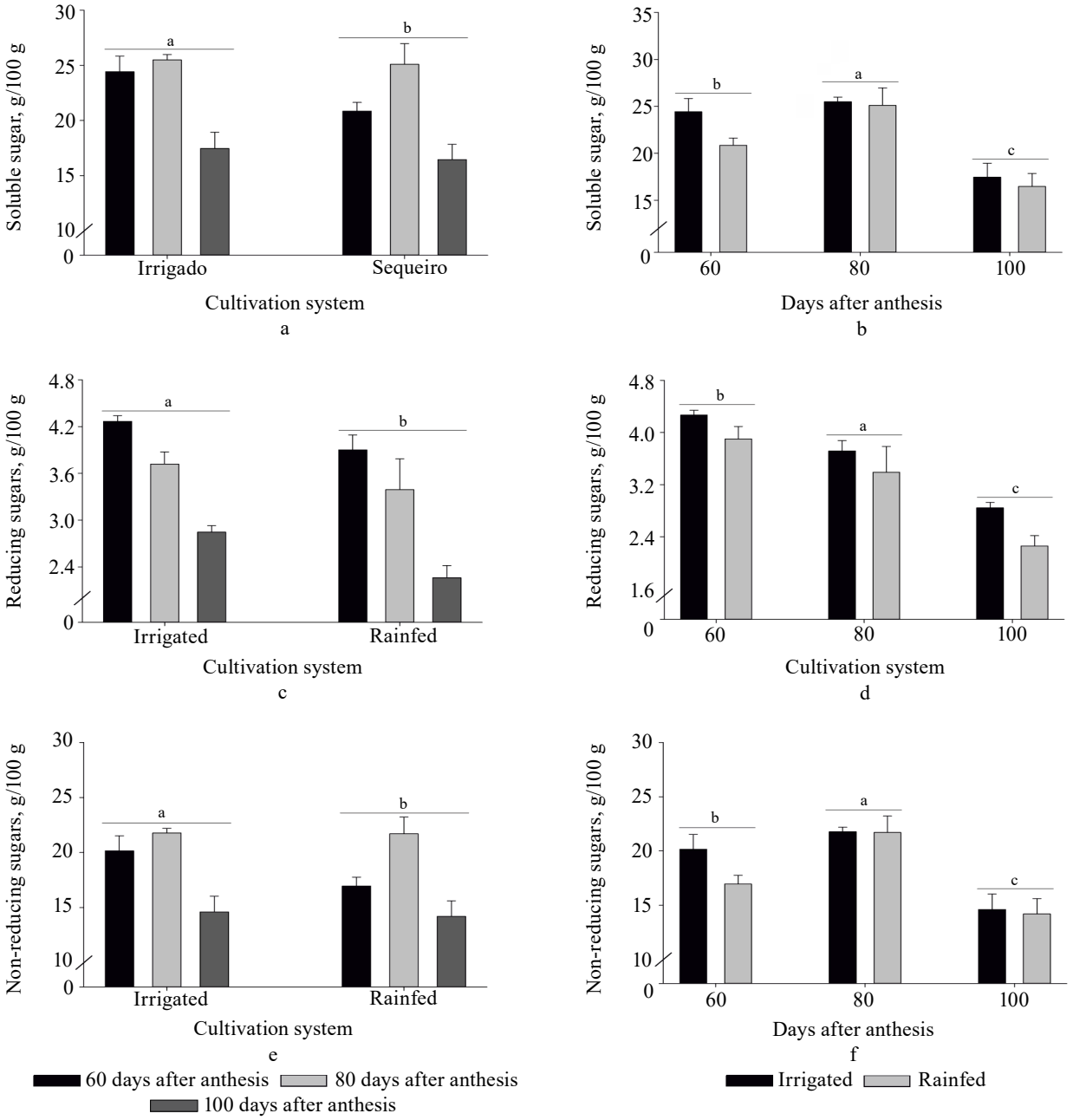
The concentration of H^+ ions showed an isolated effect for the second factor, i. e., the harvest time (Fig. 6b). The mean value for the flours produced at 60 days after anthesis was 42% higher than in the other harvest times, which were statistically equal. The inverse behavior to pH (Fig. 6a) observed for this variable was expected because lower pH values corresponded to higher concentrations of H^+ ions [52].

The soluble sugars in the analyzed flour samples showed isolated effects for both cultivation systems (Fig. 7a) and harvest times (Fig. 7b). The flours made from fruit peels cultivated with irrigation had a higher concentration of soluble sugars (7%) compared to those produced under rainfed conditions (Fig. 7a).

The increase in soluble sugars content in the flours made from fruits cultivated under irrigation may be due to irrigation being a crucial factor for producing high-quality fruits. Irrigation promotes an increase in soluble solids, sugars, and other constituents because it can enhance plant development [53]. Regarding harvest times (Fig. 7b), the results demonstrated a higher concentration of soluble sugars in the flours produced from fruit peels harvested 80 days after anthesis, being 10% higher than those harvested 60 days and 32% higher than those harvested 100 days after anthesis. This concentration possibly occurred due to fruit ripening, which, when complete, accumulated various constituents, such as soluble sugars. Additionally, starch hydrolysis into sugars contributed to this concentration. The soluble sugars content found in this study for *P. cincinnata* fruit peel flours was lower than the 26.11 g/100 g reported by Santos *et al*. [54] for cashew peduncle flour (*Anacardium occidentale* L.).

The values for reducing sugars showed differences when analyzed for isolated effects (Fig. 7c, 7d). Regarding cultivation systems (Fig. 7c), the flours made from fruit peels irrigated with water had higher values (11%) than those produced from fruits cultivated under rainfed conditions. The increase in these values with irrigation treatment mirrored what was observed for soluble sugars (Fig. 7a), highlighting irrigation as a factor that can enhance fruit yield by increasing their physicochemical constituents and improving quality [53].

The difference in reducing sugars across harvest times (Fig. 7d) showed a decrease as harvest and fruit maturation progressed. The concentration of these sugars in the flours obtained at 60 days after anthesis was higher compared to those at 80 days (13% lower) and 100 days (37% lower) after anthesis. The data



Cultivation systems followed by the same lowercase letter and harvest times followed by the same uppercase letter do not differ from each other by Tukey's test at a 5% probability level

Figure 7 Soluble sugars (a, b), reducing sugars (c, d), and non-reducing sugars (e, f) in *Passiflora cincinnata* Mast. fruit peel flour, irrigated vs. rainfed and harvested at different harvest times

indicated a predominance of non-reducing sugars in the flours produced at 80 and 100 days after anthesis. This carbohydrate is considered reducing due to the free hydroxyl group on the numerical carbon available for reactions, including glucose and fructose [55].

The non-reducing sugars differed when analyzed separately for the treatments (Fig. 7e, 7f). Regarding treatment one (Fig. 7e), the values observed in flours made from fruit peels irrigated with water were higher (6%) compared to rainfed cultivation. This behavior was similar to the other sugars analyzed, where the irrigated treatment showed higher sugar values in the flours compared to rainfed cultivation. The evaluations of non-reducing sugars and total soluble sugars yielded similar results, indicating that the soluble sugars present in *P. cincinnata* fruit peel flours were mostly non-reducing sugars.

When considering the effect of harvest times (Fig. 7f), the flours made from fruit peels harvested at 80 days after anthesis were higher in sugar than those harvested at 60 (14% higher) and 100 (33% higher) days after anthesis. The increase in sugar content in the flours produced at 80 days after anthesis may be associated with the degradation of pectin and cellulose, which were used during ripening for the biosynthesis and accumulation of sugars [56].

Table 3 Ascorbic acid content in *Passiflora cincinnata* Mast. fruit peel flours, mg/100 g

Harvest time, days after anthesis	Cultivation system	
	Irrigated	Rainfed
60	2.68	2.87
80	2.87	3.05
100	2.79	2.83

Bioactive compounds. The content of ascorbic acid present in the flours obtained from different cultivation systems and harvest times ranged between 2.68 and 3.05 mg/100 g, with no statistically significant differences (Table 3). The values found in this study were lower than the mean values reported by [57] for *P. cincinnata* peel (28.07 mg/100 g) and by [58] for the pulp of the same species (23.30 mg/100 g). This difference in values may be attributed to the fact that ascorbic acid in the material can undergo degradation during processing, as this constituent is thermodynamically unstable [59]. Consistently, vitamin C can be considered the most sensitive of all vitamins. It can be lost as a result of lipid oxidation or high-temperature utilization [60].

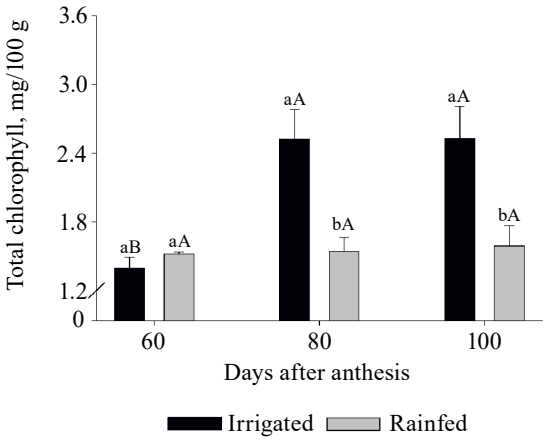
The total chlorophyll content showed a significant interaction between the cultivation system and the harvest time. The cultivation systems resulted in statistically equal values for this variable for the flours produced from fruits harvested at 60 days. However, for the flours produced at other harvest times, the irrigated treatment resulted in higher values compared to rainfed cultivation, being 38% higher at 80 days and 37% higher at 100 days after anthesis (Fig. 8).

Xavier *et al.* [61], who analyzed umbu peel flour (*Spondias tuberosa* Arruda Cam.), obtained values higher than 5.14 mg/100 g for this variable. Chlorophylls are green pigments that play a significant role in photosynthesis, being responsible for capturing light energy. They are also bioactive compounds that can enhance the nutritional value of food [62, 63]. In our research, carotenoids showed an isolated effect for harvest times. The flours produced at 60 days after anthesis had higher concentrations (18%) compared to those produced at 80 and 100 days after anthesis (Fig. 9a).

Macêdo *et al.* [64] also found a reduction in the carotenoid content in mandacaru fruits as they matured. Carotenoids are bioactive compounds widely distributed in nature, holding a prominent position among naturally occurring pigments [65]. They possess various physiological properties with beneficial effects on human health.

The content of flavonoids in the flours varied significantly across the harvest times (Fig. 9b). The flours produced at 80 and 100 days after anthesis showed statistically similar and higher concentrations of flavonoids, being 50% greater compared to those produced at 60 days after anthesis.

The flavonoid content in the *P. cincinnata* peel flours obtained in this study was higher than that in [66], who analyzed the pulp of ripe maracuja-azedo (*Passiflora te-*



Cultivation systems followed by the same lowercase letter and harvest times followed by the same uppercase letter do not differ from each other by Tukey's test at a 5% probability level

Figure 8 Total chlorophyll content in *Passiflora cincinnata* Mast. fruit peel flour

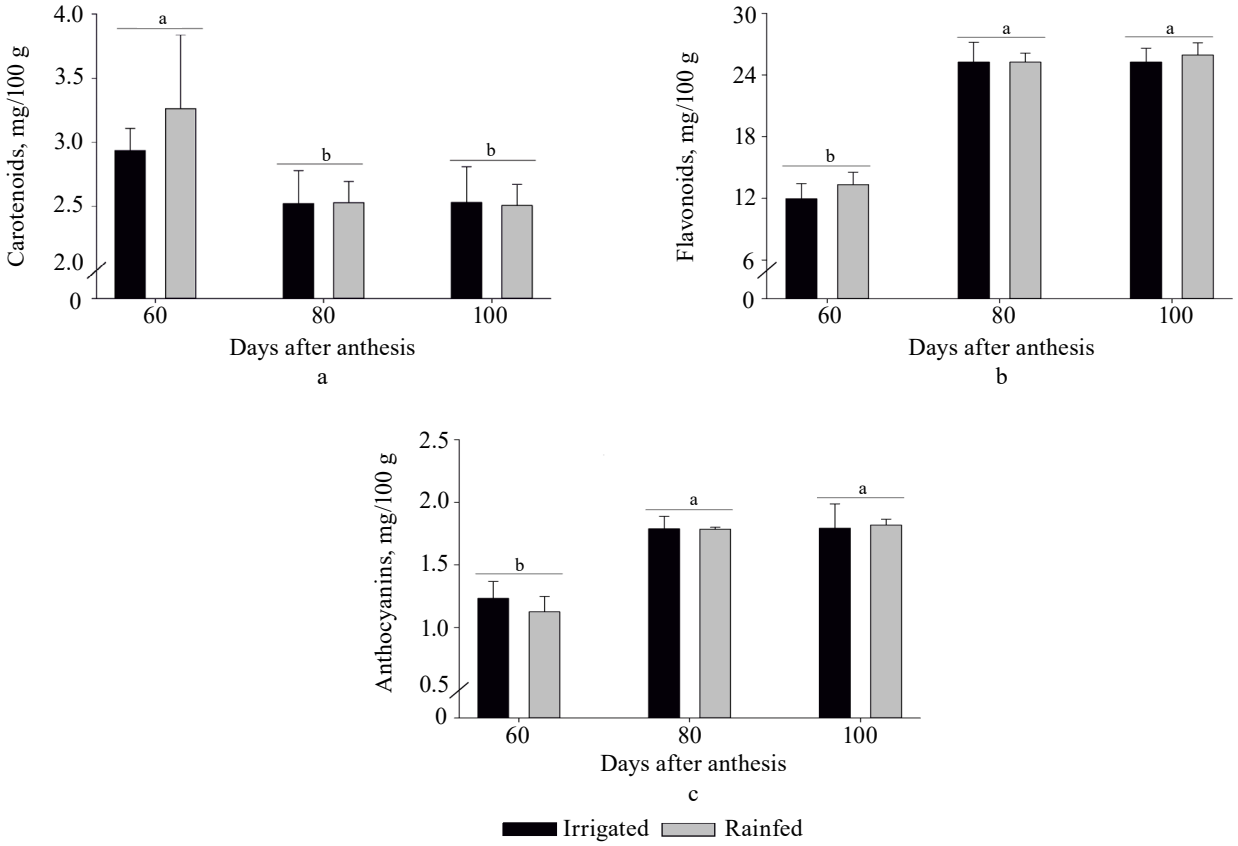
nuifila Killip) fruits (10.53 mg/100 g). Foods containing flavonoids support the proper functioning of energy metabolism, modifying anthropometric and biochemical factors, aiding in obesity prevention, and affecting the flavor and aroma of foods [67, 68].

Anthocyanin levels showed differences when analyzing the isolated effect of harvest times (Fig. 9c). The lowest concentration was observed in the flours produced at 60 days after anthesis; they differed from those produced at 80 and 100 days after anthesis, which showed higher levels (35%) for this variable. This behavior was similar to that observed for flavonoids as they share nearly the same biosynthetic pathway.

The phenolic compounds exhibited differences when analyzed separately for cultivation systems and harvest times (Fig. 10a, 10b). Regarding the cultivation systems (Fig. 10a), the highest concentration of these compounds belonged to the flours made from fruit peels cultivated under rainfed conditions, being 7% higher compared to the irrigated treatment. The increase in the content of these compounds for the rainfed cultivation samples possibly occurred due to the signaling of stress, which enhanced the production of secondary metabolites to counteract adverse environmental factors. These compounds are associated with plant defense mechanisms and various biochemical and physiological processes [69].

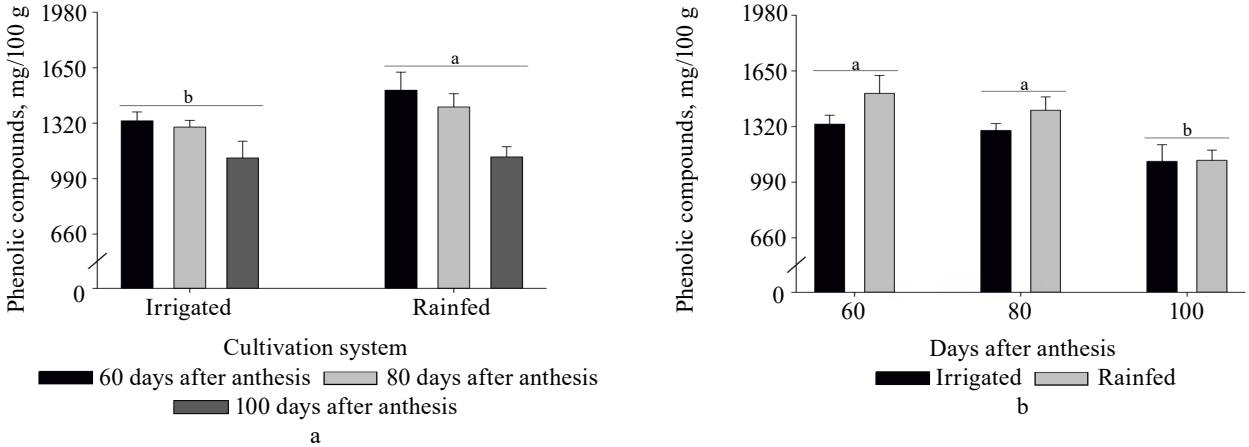
In addition to phenolic compounds being secondary metabolites involved in plant adaptation to environmental conditions, these compounds have gained prominence due to their various bioactive properties. They contribute significantly to the nutritional value of foods and benefit the food industry with their remarkable antioxidant capacity [69].

Regarding the harvest times (Fig. 10b), the values obtained for the flours produced at 60 and 80 days after anthesis were statistically equal and higher (21%) than the value in the flour produced at 100 days after an-



Cultivation systems followed by the same lowercase letter and harvest times followed by the same uppercase letter do not differ from each other by Tukey's test at a 5% probability level

Figure 9 Carotenoids (a), flavonoids (b), and anthocyanins (c) in *Passiflora cincinnata* Mast. fruit peel flour, irrigated vs. rainfed and harvested at different harvest times

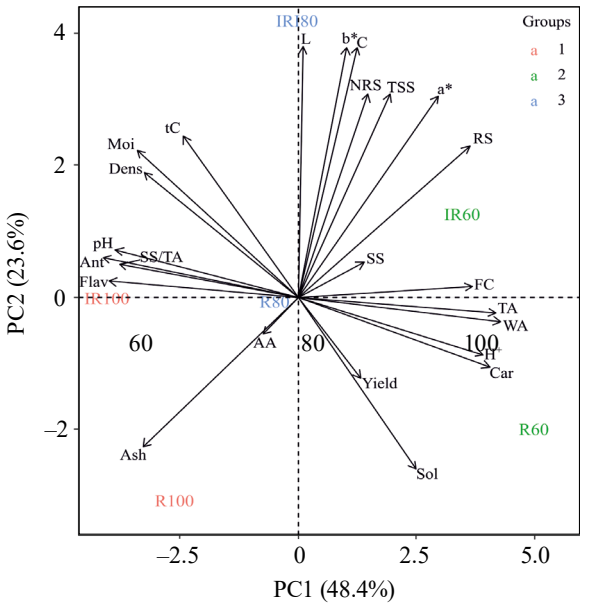


Means followed by same lowercase letter do not differ from each other by Tukey's test at a 5% probability level

Figure 10 Phenolic compounds of *Passiflora cincinnata* Mast. fruit peel flour, irrigated vs. rainfed (a) and harvested at different harvest times (b)

thesis, which showed a reduced level of phenolic compounds. Seraglio *et al*. [70] also reported a decrease in phenolic compound levels with fruit maturation for various fruits, e. g., guabiju (*Myrcianthes pungens*), jabuticaba (*Myrciaria cauliflora*), and jambolão (*Syzygium cumini*).

According to Fawole & Opara [71], the decrease in the amount of phenolic compounds can result from the oxidation of polyphenols by the enzyme polyphenol oxidase during fruit maturation. Nascimento *et al.* [72] also obtained a high value for phenolic compounds (1,816.4 mg/100 g) when analyzing green bell pepper flour.



AA – ascorbic acid; Flav – flavonoids; Ant – anthocyanins; Moi – moisture content; Sol – solubility; C – chromaticity; Car – carotenoids; L – luminosity; NRS – non-reducing sugars; and SS – soluble sugars

Figure 11 Principal component analysis for factors and variables analyzed in *Passiflora cincinnata* Mast. fruit peel flour from irrigated vs. rainfed cultivation and harvested at different harvest times

This finding is interesting because these compounds are antioxidants and add significant value to the product.

We conducted a Principal Component Analysis (PCA) to examine the correlations between the factors and variables (Fig. 11). The first two principal components (PC1 and PC2) accounted for 72% of the total variance, with PC1 explaining 48.4% and PC2 explaining 23.6%. Based on the PCA results, we identified three distinct groups. The first group consisted of wild passion fruit peel flour treatments from both irrigated and rainfed cultivation at 100 days after anthesis. The second group included samples from 60 days after anthesis under both cultivation conditions. The third group comprised samples harvested at 80 days after anthesis, regardless of irrigation treatment.

The PCA results (Fig. 11) demonstrated clear associations between the harvest times and the analyzed variables. At 100 days after anthesis, the flour from irrigated and rainfed cultivations exhibited similarities in ash content and ascorbic acid. Flavonoids, anthocyanins, pH, and the SS/TA ratio correlated more strongly with irrigated cultivation at 100 days after anthesis. The moisture content also showed a relationship with these variables but exhibited an inverse pattern compared to the solubility, yield, carotenoids, and hydrogen ions, which were more strongly associated with the 60-day harvest. The luminosity, coordinate *b**, chromaticity, non-reducing sugars, and soluble sugars were more closely linked to irrigated cultivation at 100 days after anthesis. The harvest time and cultivation system significantly affected the physicochemical properties of *P. cincinnata* peel flour, with later harvests showing greater correlations with certain bioactive compounds and colorimetric attributes while earlier harvests exhibited stronger associations with yield-related variables.

CONCLUSION

The drying process of *Passiflora cincinnata* Mast. fruit peels cultivated under irrigation and rainfed conditions at different harvest times resulted in flours with a low water activity and a tendency towards yellow coloration.

The highest concentrations of yield, soluble solids, soluble sugars, flavonoids, chlorophyll, and phenolic compounds belonged to the flour samples produced from the fruits harvested 80 days after anthesis, indicating this as the optimal period for producing *P. cincinnata* fruit peel flour.

Phenolic compounds were particularly well preserved in the flour samples produced from rainfed cultivation. These flours exhibited antioxidant potential, showing good prospects as functional food ingredients and thus enhancing the range of healthy food products.

CONTRIBUTION

The authors were equally involved in writing the manuscript and are equally responsible for any potential plagiarism.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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