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Spray-Dried Whole Red Pitaya (*Hylocereus costaricensis*): A Potential Source of Bioactive Compounds for Food Applications

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Abstract

Pitaya is a tropical fruit widely recognized for its intense coloration and abundance of bioactive compounds and natural pigments, associated with antioxidant properties and potential functional applications. However, its high moisture content and structural fragility make it highly susceptible to post-harvest deterioration and limit its shelf life, highlighting the need for effective preservation strategies to enable its industrial utilization. This study evaluated the production of spray-dried red pitaya (*Hylocereus costaricensis*) powder using the whole-fruit (pulp, peel, and seeds), since studies addressing entire fruit utilization remain scarce. The effects of air temperature (T), air flow rate (AF), maltodextrin concentration (M), and feed flow rate (FF) on moisture content, water activity, drying yield, bioactive compounds (total phenolic, flavonoid, ascorbic acid, and betalains), and color parameters were investigated. Spray drying successfully produced pitaya powders characterized by reduced moisture levels and water activity, satisfactory drying yield, and preserved bioactive compounds contents under selected processing conditions. The optimized spray drying conditions (T = 132.7 °C, AF = 1.51 m³/min; M = 9%, and FF = 0.55 L/h) were identified through the desirability function approach, indicating a balanced performance between drying efficiency and compound retention. Color parameters (L*, a*, b*, C*, H°, and ΔE) showed changes related to the operational conditions analyzed when compared with the fresh fruit. These findings support the valorization of the pitaya whole fruit and its use as a source of natural bioactive compounds for food applications.

Keywords: dragon fruit; *Hylocereus costaricensis*; fruit drying; spray dryer; drying yield; bioactive compounds; color



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1. Introduction

Pitaya (*Hylocereus* sp.), popularly referred to as “dragon fruit”, is an exotic fruit recognized for its vibrant appearance, distinctive flavor, and high commercial value, which has driven its increasing popularity in international markets, particularly in Europe and the United States [1–3]. Originating from Mexico, Central America, and parts of South America, this *Cactaceae* species has also gained relevance in Southeast Asia and other tropical regions, where its production has expanded in recent years, due to the growing demand for exotic fruits [4,5]. In addition to its sensory appeal, pitaya is valued for its bioactive composition, as it contains compounds such as phenolic, flavonoids, and betalain pigments, which are

associated with antioxidant activity and may contribute to the development of value-added products [6–9].

Among the different pitaya varieties, *Hylocereus costaricensis*, commonly known as red pitaya, stands out due to its red peel and bright red-purple pulp. This variety has attracted increasing attention owing to its richness in bioactive compounds, including ascorbic acid, carotenoids, polyphenols, beta-carotene, lycopene, vitamins B1, B2, B3, and E, as well as significant levels of potassium and magnesium [10–13]. Notably, its peel, often discarded, also contains relevant amounts of several bioactive compounds, highlighting the potential of whole-fruit utilization as a strategy to reduce processing waste while increasing the recovery of bioactive compounds for use as natural additives and functional ingredients [6,14,15].

The distinct functional and sensory properties of pitaya, including its mild sweet flavor and vibrant color, allow its direct consumption in fresh form and its use in a wide range of products such as yogurts, jams, ice creams, and beverages, highlighting its potential for diverse applications in the food industry. In addition, its peel can be processed as a flour substitute or raw material for natural pigments, contributing to the development of value-added food products [14–18]. However, despite its technological and commercial potential, pitaya is highly perishable, undergoing rapid post-harvest quality deterioration, including changes in acidity, flavor, and external appearance, which makes the adoption of effective preservation strategies essential for its commercialization and distribution [19–21].

From a resource utilization perspective, red pitaya processing generates significant amounts of non-edible fractions, particularly peel and seeds, which are commonly discarded despite their high content of bioactive compounds. This represents not only a loss of valuable phytochemicals but also an inefficiency in the use of agricultural biomass. In the context of circular bioeconomy strategies, the full exploitation of fruit matrices has been increasingly recognized as a relevant approach to improve resource efficiency and reduce agro-industrial waste generation [22,23]. Therefore, the use of whole fruit matrices can be seen as an opportunity to integrate nutritional valorization with more efficient use of natural resources, contributing to more sustainable processing chains without changing the intrinsic technological focus of product development.

Among food preservation technologies, drying is frequently applied to products with high moisture contents, such as fruits, by removing water through controlled heat application, which inhibits microbial proliferation and enzymatic reactions. In addition to prolonging product stability, this process facilitates the year-round availability of seasonal products and reduces costs associated with packaging, storage, handling, and transportation [24–26]. Several variables contribute to dehydration performance, such as the physical and chemical characteristics of the material, the drying method, and the operating conditions. Therefore, one of the major difficulties associated with food dehydration is to achieve an energy-efficient process while maintaining the nutritional, physical, and chemical quality of the final product [27–29].

Within the available techniques, spray drying is widely used in the food industry for the production of powdered products and microencapsulated ingredients. The process involves atomizing liquid feed into fine droplets that come into contact with heated air, promoting rapid moisture removal and powder formation [30–33]. Due to its short residence time and high drying rates, spray drying can produce powders with desirable physical properties while facilitating the preservation of heat-sensitive compounds [34,35]. However, the retention of color, flavor, and bioactive compounds depends strongly on operational conditions, such as inlet air temperature, air flow rate, feed flow rate, and the selection of appropriate carrier agents. Therefore, careful control and optimization of these parameters are essential to obtain powders with desirable quality and stability [36,37].

Although spray drying has been applied to pitaya juice, extracts, and individual fruit fractions [38–42], the utilization of the entire fruit through this technique remains largely unexplored. A review of the available literature revealed no studies reporting the spray drying of the whole pitaya fruit. This gap represents a missed opportunity for the development of more efficient processing strategies that could maximize fruit valorization and minimize waste generation. Furthermore, whole-fruit processing may simplify industrial operations by avoiding fractionation steps and enabling the simultaneous recovery of bioactive compounds naturally distributed among the pulp, peel, and seeds.

In response to this knowledge gap, the present study evaluated the feasibility of producing red pitaya powder through spray drying of the whole red pitaya fruit (pulp, peel, and seeds). The effects of critical operational parameters—inlet air temperature (T), air flow rate (AF), maltodextrin concentration (M), and feed flow rate (FF)—were systematically investigated to optimize both process yield and quality attributes of the resulting powder. Product quality was assessed through the quantification of bioactive compounds (total phenolic, total flavonoid, ascorbic acid, and total betalain content) and color parameters, contributing to the valorization of whole fruit through the production of powders rich in natural bioactive compounds for potential food applications.

2. Materials and Methods

2.1. Raw Material

Fresh pitaya fruits selected for this study were kindly provided by Pitayas Formosa, a local plantation located in the Lagoa Formosa region (18°46'44" S, 46°24'28" W), Minas Gerais, southeastern Brazil. Prior to processing, the fruits were cleaned under running water and then subjected to sanitization using a 200 ppm sodium hypochlorite solution. They were then packaged in polyethylene bags with airtight closure and maintained frozen at −18 °C until required for the experiments.

2.2. Experimental Apparatus and Procedure

The drying experiments were conducted in a laboratory-scale spray dryer (LM MSD 1.0, LabMaq, Ribeirão Preto, SP, Brazil) (Figure 1). The equipment has overall dimensions of 0.76 m × 1.80 m × 0.72 m (width × height × depth), a total mass of 180 kg, and is constructed entirely from AISI 304 stainless steel. The system comprises a drying chamber measuring 0.625 m in length and 0.20 m in diameter, equipped with a two-fluid atomizing nozzle (1.2 mm orifice) and presenting an evaporation capacity of 1.0 L·h^{−1}. A constant atomization air flow rate of 40 L·min^{−1} was employed. The feed suspension was introduced into the drying chamber by a peristaltic pump, and the resulting powder was recovered using a cyclone installed at the outlet of the system.

Within the scope of this study, the whole pitaya fruit (pulp, peel, and seeds) was used. According to the literature, bioactive compounds and nutrients in fruits are distributed not only in the pulp but also in the peel and other anatomical fractions. This is particularly relevant for pitaya, where each part contributes with different nutritional and bioactive profiles [3,6,43,44].

Prior to the drying process, the entire pitaya fruits were blended using a domestic blender (Mondial Easy Power 550 W, Barueri, Brazil) with the addition of water in a 1:1.5 ratio (pitaya mass to water mass). This homogenization step was performed to obtain a uniform suspension suitable for atomization while ensuring the simultaneous processing of all fruit fractions, consistent with the objective of evaluating whole-fruit utilization. The pitaya suspension was subsequently screened through a 24-mesh Tyler sieve to remove a negligible amount of coarse particles (>710 µm), which could cause clogging of the atomizer nozzle during the drying process [32]. Due to their small size, the pitaya seeds readily

passed through the sieve and remained in the suspension. This sieving step was performed solely to achieve the technological requirements of the dryer and did not constitute a separation of any anatomical fruit fractions. Each experiment utilized about 200 g of the obtained suspension.

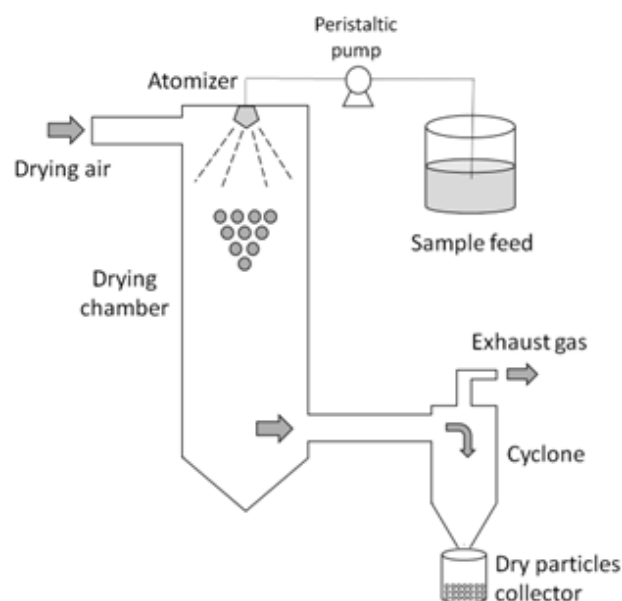


Figure 1. Spray dryer schematic figure, adapted from Silva et al. [32].

Preliminary spray-drying experiments with the prepared suspension resulted in powder exhibiting pronounced stickiness and strong adherence to the internal equipment surfaces. Raw materials characterized by high concentrations of sugars and organic acids, particularly fruits and vegetables, pose significant difficulties during conventional spray-drying conditions, thereby requiring the incorporation of carrier agents, such as maltodextrin [30,32,45]. Maltodextrin is a widely used carrier material obtained from corn starch through partial hydrolytic processing. It is frequently applied in the spray drying of sugar-rich materials because of its combination of high aqueous solubility, low viscosity, sensory neutrality, physicochemical stability, and economic viability [45–47]. Therefore, the suspension was supplemented with maltodextrin (MOR-Rex® 1910, Ingredion, São Paulo, SP, Brazil; 10 DE—dextrose equivalent) at different concentrations relative to the mass of suspension fed into the dryer. The concentration range investigated was established in experimental design, as outlined subsequently.

2.3. Experimental Design

The study employed a rotatable central composite design (CCD) consisting of four process variables and three center-point replicates, generating 27 experimental conditions. The independent variables considered in this study were: drying air temperature (T), drying air flow rate (AF), maltodextrin concentration (M), and fresh pitaya feed flow rate (FF). The coded and real values adopted for each experimental factor are summarized in Table 1. These factors were evaluated in relation to process performance and quality attributes, which were considered as response variables, including drying yield (DY), bioactive compound contents (TPC, TFC, AA, BE), and color parameters (L, a, b*, C*, H°, and ΔE).

Table 1. Coded and real values of the experimental design.

Independent Variables	−2	−1	0	+1	+2
Drying air temperature (°C)	90	110	130	150	170
Drying air flow rate (m ³ /min)	1.1	1.3	1.5	1.7	1.9
Maltodextrin concentration (%)	6%	9%	12%	15%	18%
Pitaya feed flow rate (L/h)	0.25	0.35	0.45	0.55	0.65

2.4. Moisture Analysis and Water Activity (a_w)

Wet-basis moisture content was determined for fresh and dried samples using gravimetric drying in an oven maintained at 105 ± 3 °C for 24 h, as per the standards of the Association of Official Analytical Chemists [48]. Water activity (a_w) was measured using a dew-point water activity meter (Aqualab PRE Dewpoint, Pullman, WA, USA), which determines a_w under controlled temperature conditions using an integrated infrared sensor. Water activity values were obtained on a scale ranging from 0.000 to 1.000, with a measurement precision of ± 0.001 . For each sample, analyses were performed in triplicate.

The physicochemical and microbiological stability of dried products is commonly assessed through the combined analysis of moisture content and water activity (a_w). Previous studies indicate that dried fruits with moisture levels under 10% favor the handling, processing, logistical operations, and storage. In addition, food and biological materials should typically exhibit water activity values below 0.600 to ensure microbiological stability, as the growth of bacteria, molds, and yeasts is largely inhibited beneath this threshold [49–51].

2.5. Drying Yield (DY)

For each experimental run, drying yield (DY) was calculated as the percentage of dry solids recovered from the cyclone underflow relative to the dry solids introduced into the system, with both values expressed as dry matter.

2.6. Analysis of Bioactive Compounds

The analysis of bioactive constituents in dried pitaya samples was undertaken to evaluate how the experimental conditions of spray drying influence the quality of the powders produced. The reported values correspond to the mean of three independent measurements and are presented together with their respective standard deviations.

2.6.1. Total Phenolic Content (TPC)

Total phenolic compounds were quantified according to the Folin–Ciocalteu procedure [52]. Prior to analysis, about 0.5 g of the samples were subjected to methanolic extraction for 1 h, followed by filtration to obtain the extracts used in the subsequent determinations. Gallic acid (C₇H₆O₅) was used as the reference standard calibration. Absorbance measurements were obtained at 622 nm with a V1200 spectrophotometer (VWR, Leuven, Belgium). Phenolic content was expressed as milligrams of gallic acid per 100 g of dry sample.

2.6.2. Total Flavonoid Content (TFC)

Total flavonoids were quantified according to the colorimetric procedure proposed by Zhishen et al. [53]. The methanolic extracts prepared for the determination of TPC were also used for flavonoid analysis. Rutin (C₂₇H₃₀O₁₆) was used for calibration standard. Absorbance readings were obtained at 450 nm with a V1200 spectrophotometer (VWR, Leuven, Belgium). Flavonoid content was expressed as milligrams of rutin per 100 g of dry matter.

2.6.3. Ascorbic Acid Content (AA)

Ascorbic acid or vitamin C content ($C_6H_8O_6$) was quantified by a titrimetric procedure based on the reduction of standardized 2,6-dichloroindophenol ($C_{12}H_7NCl_2O_2$) in an oxalic acid medium ($C_2H_2O_4$) [48]. Prior to analysis, about 2.0 g of the samples were macerated in distilled water, and an aliquot of the resulting extract was mixed with oxalic acid and subjected to titration. The results were reported as milligrams of ascorbic acid per 100 g of dry matter.

2.6.4. Betalain Content (BE)

Betalain content was quantified following the method described by Tang and Norziah [54], with minor modifications. For the analysis, about 1.5 g of the sample was diluted and homogenized in 250 mL of distilled water, and then filtered through filter paper. Next, the absorbance was determined spectrophotometrically at 536 nm. Results were presented in mg of betalain/100 g of sample on a dry matter and the calculation was performed using Equation (1):

$$BE = \frac{Abs \cdot F \cdot MM \cdot 10^8}{\epsilon \cdot l \cdot (1 - h)} \quad (1)$$

where BE is the betalain content; Abs is the absorbance measured at 536 nm; F is the sample preparation correction factor, calculated as the ratio between the mass of water used for extraction and the total mass of the suspension ($250/(250 + 1.5) = 0.994$); MM is the molar weight of betanin (550 g/mol); ϵ is the molar extinction coefficient of betanin ($60,000 \text{ L} \cdot \text{mol}^{-1} \cdot \text{cm}^{-1}$); l is the optical path length of the cuvette (1.24 cm); and h is the moisture fraction (determined according to Section 2.4). The factor 10^8 was used to convert the calculated concentration from $\text{mg} \cdot \text{L}^{-1}$ to mg per 100 g in dry matter.

2.7. Color

Color analysis was performed aiming to determine how spray drying conditions affected the visual quality of the samples. Color measurements can be performed using different instruments, with colorimeters providing measurements that closely resemble human visual perception [55,56]. Thus, the color of fresh and dried samples was obtained using a digital colorimeter (Konica Minolta CR-400/410, Tokyo, Japan) operating within the CIELab color space (L^* , a^* , b^*), as defined by the International Commission on Illumination (CIE) [57]. In this system, L^* represents lightness (0 = black, 100 = white), a^* represents the red (+) to green (−) axis, and b^* represents the yellow (+) to blue (−) axis.

Based on the L^* , a^* , and b^* values, chroma (C^*), hue angle (H°) and total color difference (ΔE) were also calculated. C^* denotes color saturation, where higher values correspond to more vivid and intense colors, while lower values indicate reduced saturation and a more muted appearance. The H° defines the chromatic tone angle (0° = red, 90° = yellow, 180° = green, and 270° = blue). The ΔE was used to quantify color changes relative to the fresh sample. Values below 1 are generally considered imperceptible to the human eye, whereas increasing ΔE values indicate progressively more noticeable color differences [57,58]. These parameters were defined according to Equations (2), (3), and (4), respectively, where L^1 , a^1 , and b^1 represent the CIE L^* values of the fresh sample as the reference color.

$$C = \sqrt{(a^*)^2 + (b^*)^2} \quad (2)$$

$$H^\circ = \tan^{-1}(b^*/a^*) \quad (3)$$

$$\Delta E = \sqrt{(L^1 - L^*)^2 + (a^1 - a^*)^2 + (b^1 - b^*)^2} \quad (4)$$

2.8. Statistical Analysis

All physicochemical, bioactive compounds, and color analyses were performed in triplicate (analytical replicates), and mean values were used for statistical evaluation. Experimental error and process variability were estimated from the replicated central points included in the Central Composite Design (CCD).

Data were evaluated using multifactorial analysis of variance (ANOVA) with a 95% confidence level. Response surface models were developed through multiple regression analysis to describe the effects of independent variables on the responses [59]. All statistical analyses were performed using Statistica v.12 software (Statsoft).

Additionally, for drying yield (DY) and bioactive compounds (TPC, TFC, AA, and BE), a process optimization was carried out using the desirability function approach. Desirability analysis is a statistical method that optimizes processes by integrating multiple responses or performance criteria into a unified composite measure. Commonly employed in engineering, market research, and quality control, it enables the maximization or minimization of a response by converting it into a composite function with values ranging from 0 (completely undesirable) to 1 (fully desirable) [60,61].

3. Results and Discussion

3.1. Drying Performance

Spray-dried pitaya powder exhibited a fine and homogeneous appearance with a characteristic pink coloration, as can be seen in Figure 2, indicating effective atomization and particle formation under the applied drying conditions. Table 2 summarizes the final moisture content, water activity (a_w), and drying yield (DY) obtained across the experimental runs.

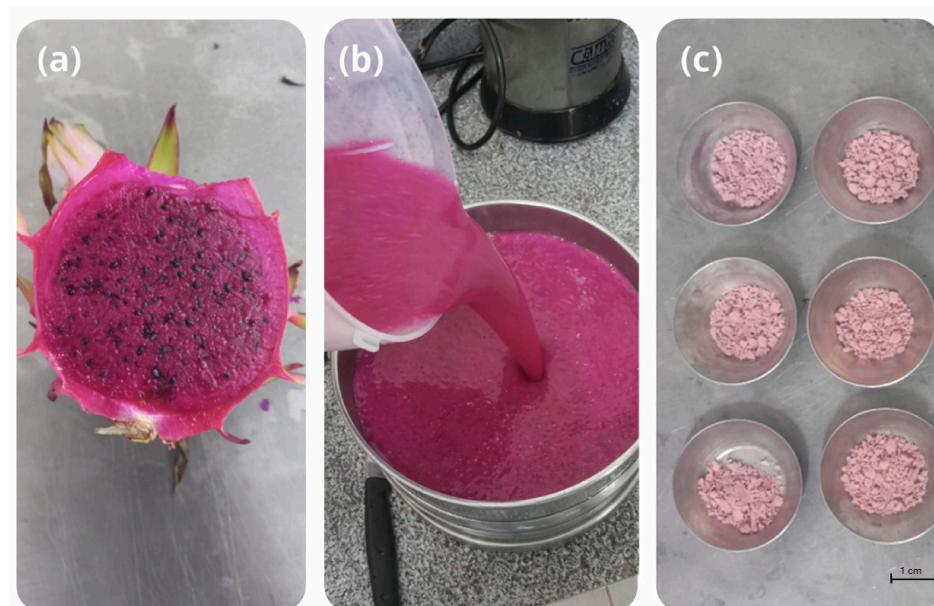


Figure 2. Pitaya fruit (a), pitaya suspension (fresh material) (b), and examples of powders produced after spray drying (c).

The fresh pitaya showed a high initial moisture content of $89.17 \pm 0.03\%$ (wet basis) and a water activity (a_w) of 0.963. After spray drying, the moisture content of the powders ranged from 0.95 to 4.66%, while a_w varied between 0.111 and 0.335. The pronounced reduction in both parameters demonstrates the high efficiency of the process, independently of the experimental conditions applied (T, AF, M, and FF). In general, foods with water activity values below 0.600 are considered microbiologically stable and are not susceptible

to deterioration caused by microorganisms or undesirable chemical reactions [49–51], further confirming the effectiveness of spray drying for preservation of this fruit.

Table 2. Experimental results of final moisture content, water activity (a_w), and drying yield (DY).

Exp.	T (°C)	AF (m ³ /min)	M (%)	FF (L/h)	Final Moisture (%)	Water Activity (a_w)	Drying Yield (%)
1	110	1.3	9.0	0.35	2.67	0.279	38.79
2	110	1.3	9.0	0.55	2.50	0.290	33.30
3	110	1.3	15.0	0.35	2.97	0.292	39.86
4	110	1.3	15.0	0.55	4.19	0.335	35.43
5	110	1.7	9.0	0.35	4.21	0.253	42.15
6	110	1.7	9.0	0.55	3.24	0.275	40.29
7	110	1.7	15.0	0.35	2.81	0.262	37.41
8	110	1.7	15.0	0.55	2.99	0.250	29.34
9	150	1.3	9.0	0.35	1.98	0.249	31.87
10	150	1.3	9.0	0.55	3.24	0.215	31.31
11	150	1.3	15.0	0.35	1.89	0.175	45.55
12	150	1.3	15.0	0.55	3.39	0.154	45.55
13	150	1.7	9.0	0.35	4.66	0.191	36.88
14	150	1.7	9.0	0.55	2.60	0.127	39.41
15	150	1.7	15.0	0.35	1.91	0.129	48.12
16	150	1.7	15.0	0.55	2.09	0.111	47.08
17	90	1.5	12.0	0.45	3.89	0.187	36.95
18	170	1.5	12.0	0.45	1.86	0.146	50.01
19	130	1.1	12.0	0.45	2.94	0.162	31.47
20	130	1.9	12.0	0.45	2.09	0.207	50.91
21	130	1.5	6.0	0.45	3.73	0.216	25.68
22	130	1.5	18.0	0.45	2.21	0.147	42.13
23	130	1.5	12.0	0.25	2.68	0.163	50.25
24	130	1.5	12.0	0.65	2.69	0.165	44.80
25	130	1.5	12.0	0.45	1.31	0.158	43.37
26	130	1.5	12.0	0.45	0.95	0.160	45.21
27	130	1.5	12.0	0.45	1.26	0.163	41.85

The significant reduction in water content also enhances product stability during storage and transportation, reducing post-harvest losses, a major challenge in tropical fruit supply chains [24,25]. In this context, the conversion of whole pitaya fruit into a stable powdered ingredient supports more efficient use of agricultural resources by enabling the utilization of both edible and non-conventionally consumed fractions, thereby adding value to the raw material and expanding its potential applications in food systems.

Drying yield (DY) ranged from 25.68% to 50.91% across the experimental results, indicating a strong influence of the four studied variables on the amount of pitaya powder produced. In spray drying processes, wall deposition represents a major operational challenge, as it is affected by multiple processing parameters and can significantly reduce both product recovery and quality, in addition to increasing production and maintenance costs [36,62]. A preliminary evaluation of Table 2 shows that higher DY values were generally associated with experiments conducted close to the intermediate conditions (center point) of the experimental design, suggesting a balance between drying rate and particle stickiness under intermediate conditions. This trend is exemplified by the higher yields observed in Experiments 20, 23 and 18 (50.91, 50.25, and 50.01%, respectively), compared to the lower DY values obtained in Experiments 21, 8, and 10 (25.68%, 29.34% and 31.31%, respectively).

Based on the statistical analysis of the DY, a prediction equation was obtained through multiple regression (Equation (5), $R^2 = 0.9261$). In this equation, as well as in Equations (7)–(12) related to bioactive compounds content and color parameters analysis, the independent variables are presented in coded form according to Equation (6), as can be seen below.

$$DY = 41.95 + 1.61x_1 + 5.79x_2 - 5.94x_2^2 + 3.45x_3 - 2.49x_3^2 - 1.36x_4 + 0.92x_4^2 + 1.72x_1x_2 + 3.52x_1x_3 + 1.11x_1x_4 - 2.33 \cdot x_2 \cdot x_3 \quad (5)$$

where

$$x_1 = \frac{(T(^{\circ}\text{C}) - 130^{\circ}\text{C})}{20^{\circ}\text{C}} \quad x_2 = \frac{(AF(\frac{\text{m}^3}{\text{min}}) - 1.5 \text{ m}^3/\text{min})}{0.2 \text{ m}^3/\text{min}} \quad x_3 = \frac{(M(\%) - 12\%) }{3\%} \quad x_4 = \frac{(FF(\frac{\text{L}}{\text{h}}) - 0.45 \text{ L/h})}{0.1 \text{ L/h}} \quad (6)$$

Equation (5) confirmed that all independent variables had a significant influence on the process performance (DY), with the air flow rate (x_2) being the most influential factor, followed by maltodextrin concentration (x_3), temperature (x_1) and feed flow rate (x_4). This behavior can be associated with the direct impact of air flow on droplet residence time and drying efficiency, since higher airflow enhances moisture removal and reduces particle adhesion to the dryer chamber walls [27,30,34]. Maltodextrin concentration also played a relevant role by modulating feed viscosity and glass-forming ability, which affects particle formation and reduces stickiness during drying [45–47]. In contrast, inlet temperature influences the evaporation rate and crust formation dynamics, while feed flow rate affects droplet size distribution and local humidity within the drying chamber [34–36]. Significant interaction effects between temperature and the other variables ($x_1 \cdot x_2$, $x_1 \cdot x_3$, and $x_1 \cdot x_4$), as well as between air flow rate and maltodextrin concentration ($x_2 \cdot x_3$), indicate that DY is also governed by coupled heat and mass transfer phenomena rather than only for isolated effects.

Figure 3 presents the response surfaces generated from the experimental results, in which the other variables were fixed at their central levels. As shown in Figure 3a that increasing the drying temperature (T) combined with intermediate air flow rates (AF) between 1.4 and 1.6 m^3/min , resulted in improved process performance. Higher temperatures enhance heat and mass transfer rates, promoting rapid moisture evaporation and promote faster crust formation on the droplets surface, reducing particle stickiness. This, in turn, minimizes powder deposition on the internal surfaces of the dryer, thereby improving product recovery and overall drying efficiency [30,36].

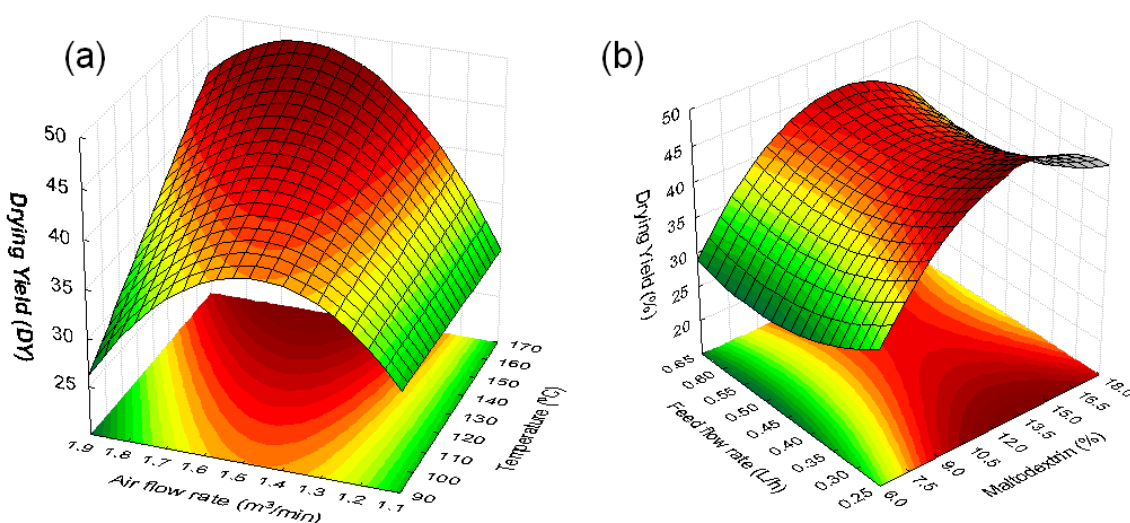


Figure 3. Drying yield (DY) response surfaces: (a) temperature (T) $\times$ air flow rate (AF) and (b) maltodextrin concentration (M) $\times$ feed flow rate (FF).

Regarding maltodextrin content (Figure 3b), concentrations between 12 and 15% resulted in the highest drying yield (DY), suggesting an optimal balance between droplet stabilization and particle formation efficiency within an appropriate carrier concentration range [31,34]. In contrast, the feed flow rate (FF) exhibited a less pronounced effect on DY under the studied conditions. Previous studies, such as that of Shofinita et al. [41], also emphasize the importance of maltodextrin in spray drying processes of pitaya. In this context, identifying an optimal concentration range is essential not only to maximize process efficiency, but also to minimize excessive carrier incorporation in the final product, preserving its compositional quality.

Moreover, the observed drying yield values, particularly under optimized conditions, indicate improved solid recovery and reduced process losses, reflecting enhanced raw material utilization. The identification of operational conditions that minimize wall deposition is relevant for improving process efficiency and reducing operational costs [36,45,46]. Overall, these results highlight the importance of spray drying parameters for efficient resource use in whole-fruit valorization strategies, contributing not only to process efficiency but also to a more complete utilization of the biomass, including fractions that would otherwise be discarded, thereby improving the overall resource efficiency of the system.

Nevertheless, beyond drying yield, it remains essential to assess the impact of processing parameters on the final product quality attributes. In particular, the effect of the drying conditions on bioactive compounds retention and color should be carefully considered, as discussed in the subsequent sections.

3.2. Bioactive Compounds

3.2.1. Total Phenolic Content (TPC)

Pitayas is known to contain a wide range of phenolic compounds, including phenols, coumarins, flavonoids, and tannins, which contribute to its antioxidant capacity [7,10]. Both pulp and peel fractions have been reported as important sources of polyphenols, with *Hylocereus costaricensis* typically exhibiting higher phenolic content and antioxidant activity, which may be associated with lower LDL cholesterol levels and reduced cardiovascular diseases risk [6,13,14,63,64]. Consistent with these findings, the total phenolic content (TPC) observed in the fresh whole red pitaya in the present study reached 1071.01 ± 32.54 mg gallic acid/100 g of dry matter, that was substantially higher than values reported in studies evaluating only the fruit pulp [65,66], highlighting the contribution of non-edible fractions to the overall phenolic profile.

TPC values determined after the experiments (according to the conditions listed in Table 2) are presented in Figure 4. Compared to fresh pitaya, a pronounced decrease in total phenolic compounds was observed, as initially expected due to the addition of maltodextrin during spray drying, once this carrier agent contributes to a dilution effect by increasing the total solid content of the final powder collected [32]. The TPC values ranged from 50.02 to 100.42 mg of gallic acid per 100 g of sample on a dry basis, as verified in Experiments 11 and 21, respectively, indicating that processing conditions significantly influenced phenolic retention in the powders. This finding indicates the importance of using appropriate process parameters to maximize phenolic retention in the final product.

Regression analysis of the experimental data yielded Equation (7) ($R^2 = 0.9603$), indicating that all four process variables influenced TPC. Maltodextrin concentration (x_3) exhibited the most pronounced negative effect on TPC, which can be associated with both dilution effects and changes in the solid matrix composition, as previously related. Temperature (x_1) also showed a negative influence, exhibited a considerably weaker negative effect in its linear term compared to maltodextrin, which is consistent with the thermolabile nature of phenolic compounds and their susceptibility to thermal degradation during spray

drying [39,41]. In contrast, air flow rate (x_2) and feed flow rate (x_4) exhibited nonlinear (quadratic) effects, suggesting that TPC retention is also governed by coupled heat and mass transfer phenomena, where variations in residence time, droplet size, and drying kinetics influence the extent of phenolic degradation [38,42].

$$\text{TPC} = 78.16 - 2.57 \cdot x_1 - 5.91 \cdot x_2^2 - 21.99 \cdot x_3 + 2.20 \cdot x_4^2 \quad (7)$$

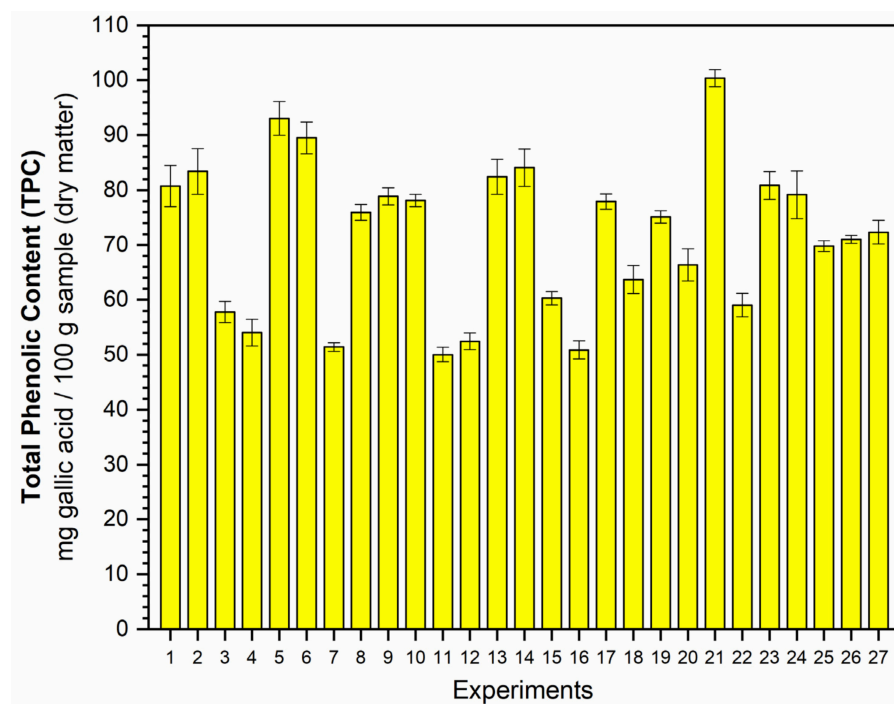


Figure 4. Total Phenolic Content (TPC) results.

The response surface analysis (Figure 5) shows that intermediate drying air flow rates (AF), close to $1.5 \text{ m}^3/\text{min}$, combined with temperatures (T) below 130°C , favored higher TPC values, as observed for example, in Experiments 21 and 17 (100.72 mg and 77.93 mg gallic acid per 100 g in dry basis, respectively) (Figure 4). This behavior can be explained by the balance between heat exposure and residence time during spray drying. At lower temperatures, the extent of thermal degradation and oxidation of phenolic compounds is reduced, while intermediate airflow conditions may provide sufficient drying efficiency without excessively prolonging particle exposure within the drying chamber [41,42]. Similar trends have been reported by Lee, Wu, and Siow [39] for pitaya, who demonstrated the thermal sensitivity of phenolic compounds and associated higher drying temperatures with their degradation. According to these authors, exposure to elevated temperatures may promote oxidation and structural degradation of phenolic compounds, leading to a reduction in their concentration.

3.2.2. Total Flavonoid Content (TFC)

Flavonoids are a major subclass of plant phenolic compounds, widely associated with antioxidant properties and contributing to key characteristics such as pigmentation and flavor in fruits. In addition, to their technological relevance, these compounds are recognized for their biological activities, including anti-inflammatory and immunomodulatory effects [67,68]. In pitaya, flavonoids such as rutin, quercetin, kaempferol, and isorhamnetin have been reported, with higher concentrations typically found in the peel fraction, which is often underutilized despite its functional potential [66,69]. The total flavonoid content (TFC) results obtained after the experiments are presented in Figure 6 (see conditions in Table 2).

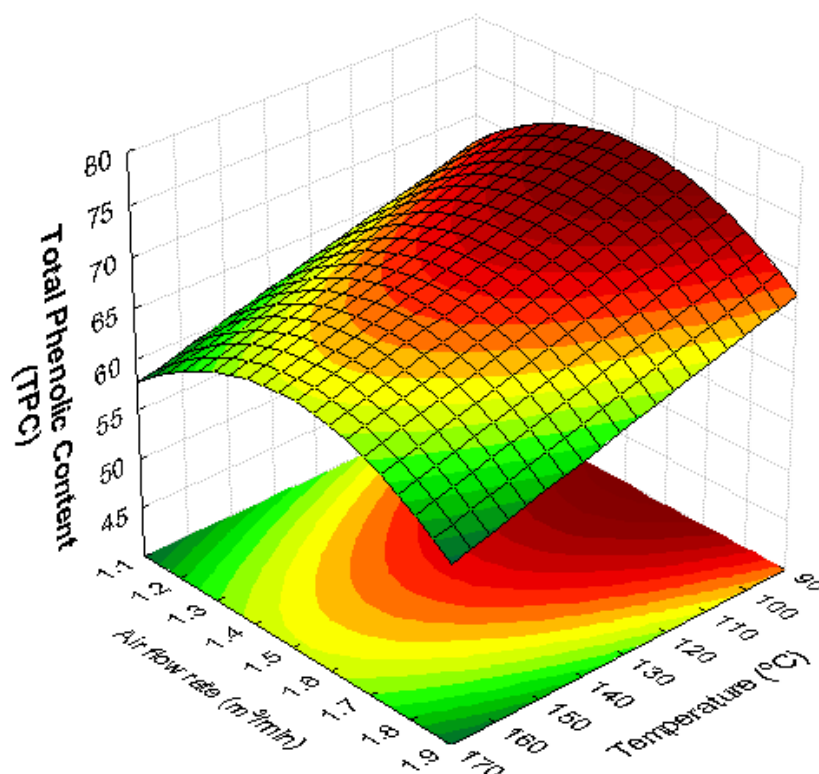


Figure 5. Total phenolic content (TPC) response surface: air flow rate (AF) $\times$ temperature (T).

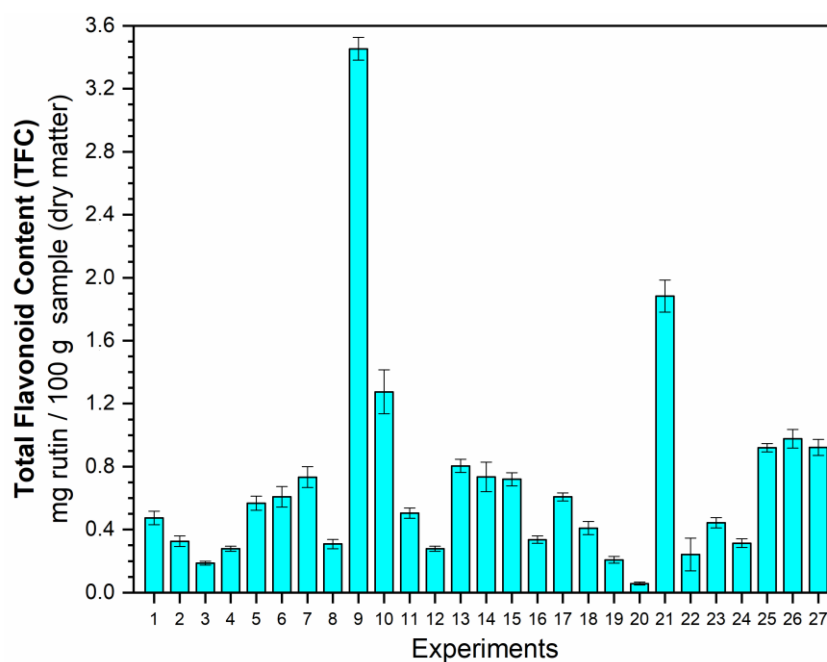


Figure 6. Total Flavonoid Content (TFC) results.

TFC showed a similar trend to that observed for TPC results, with spray drying leading to a marked decrease in total flavonoid content compared to fresh sample, which presented 42.27 ± 1.74 mg of rutin per 100 g of dry sample. This reduction can be attributed, in a similar form, to a combination of dilution effects caused by maltodextrin addition and the thermal sensitivity of flavonoid compounds during the drying process. However, a pronounced variation in TFC was observed depending on the experimental conditions, with values ranging from 0.06 to 3.45 mg of rutin per 100 g (dry basis). These results indicate that flavonoid content was strongly influenced by the process variables, suggesting

that optimization of spray drying conditions is essential to minimize degradation and improve this compound preservation.

The prediction equation for TFC as a function of the studied variables (in coded form) is presented in Equation (8) ($R^2 = 0.9488$), showing that all independent variables were statistically significant. Among them, maltodextrin concentration (x_3) also exerted the strongest and most pronounced negative effect on TFC, which can be associated with dilution effects and changes in the solid matrix composition, since the carrier agent increases total solids without contributing flavonoid compounds. In addition, significative interactions terms were also identified, indicating that flavonoid retention is influenced by both individual and interactive effects of the process variables. These interactions reflect the complex nature of spray drying, where heat and mass transfer phenomena, together with drying kinetics, act simultaneously to determine thermal exposure and the stability of bioactive compounds [25,30,31].

$$\text{TFC} = 1.06 - 0.11x_1^2 - 0.07x_2 - 0.21x_2^2 - 0.47x_3 + 0.30x_3^2 + 0.07x_4 - 0.14x_4^2 + 0.17x_2x_3 - 0.13x_2x_4 - 0.20x_3x_4, \quad (8)$$

The highest flavonoid contents were achieved at temperatures between 120 and 150 °C combined with maltodextrin concentrations below 9% (Figure 7). This behavior is exemplified by Experiment 9, conducted at 150 °C and 9% maltodextrin concentration, which resulted in 3.45 mg of rutin per 100 g of dry basis. Elevated temperatures may enhance thermal and oxidative degradation of flavonoids, particularly under conditions of increased droplet residence time and rapid moisture removal, which can accelerate structural breakdown of these compounds [66,68]. In addition, higher maltodextrin concentrations influence flavonoid retention not only through dilution of the final powder, but also by modifying the drying matrix, which may affect the exposure and stabilization of bioactive compounds during particle formation [41].

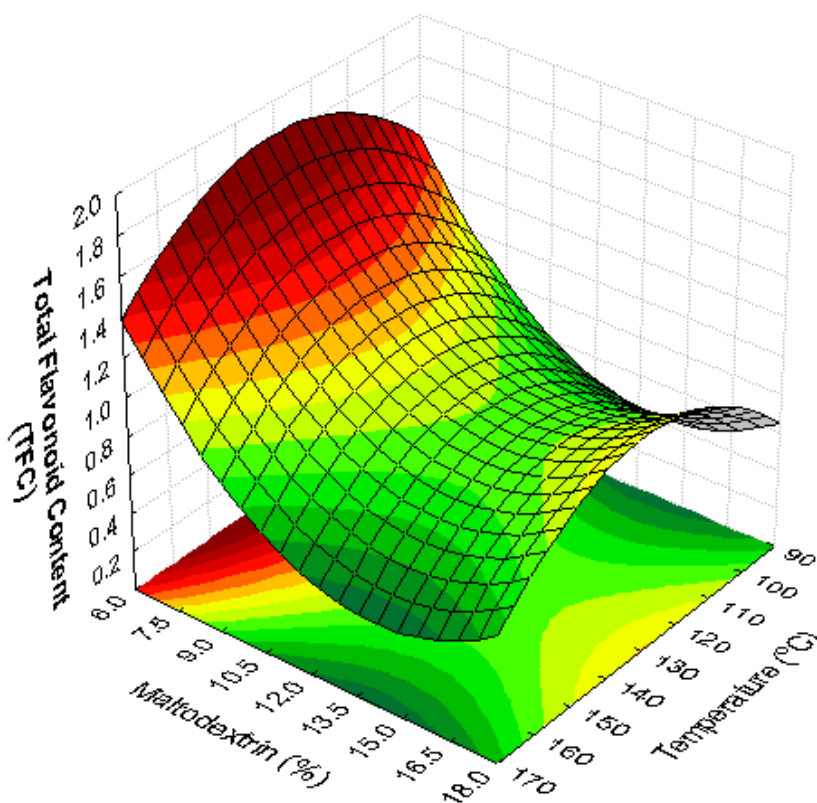


Figure 7. Total flavonoid content (TFC) response surface: temperature (T) × maltodextrin concentration (M).

The results for total flavonoid content reinforce the relevance of whole-fruit processing, particularly considering the incorporation of the peel into the spray-dried product enables the recovery of compounds that would otherwise remain underutilized, contributing to a more efficient exploitation of the fruit's biochemical potential [66,69].

3.2.3. Ascorbic Acid Content (AA)

Ascorbic acid (or vitamin C) is a key water-soluble antioxidant in foods, playing an important role in redox balance and contributing to the prevention of oxidative reactions such as enzymatic browning. Due to its high reducing capacity, ascorbic acid is preferentially oxidized in relation to other food components, thereby protecting them from oxidative damage through free radical scavenging activity [70,71]. In fruits such as pitaya, ascorbic acid content is influenced by edaphoclimatic factors and fruit maturity, which affect the overall phytochemical composition. Several studies have evaluated the ascorbic acid content in pitaya and highlighted its nutritional relevance [72–75].

The ascorbic acid (AA) content obtained in each experimental condition is presented in Figure 8. Similarly to trend of the other bioactive compounds, the AA in the produced powder showed significant variations as a function of the experimental conditions, highlighting the strong influence of processing parameters on the retention of this compound. The ascorbic acid content ranged from 62.13 to 148.99 mg per 100 g of sample on a dry matter, which is substantially lower than that of fresh pitaya (321.19 mg per 100 g dry basis). This reduction also can be attributed to the presence of maltodextrin, due to dilution effects in the final powder. However, the high susceptibility of ascorbic acid to thermal degradation and oxidative reactions during spray drying [70,71], particularly under conditions of elevated temperature and prolonged droplet exposure within the drying chamber can be responsible for AA losses in the product obtained.

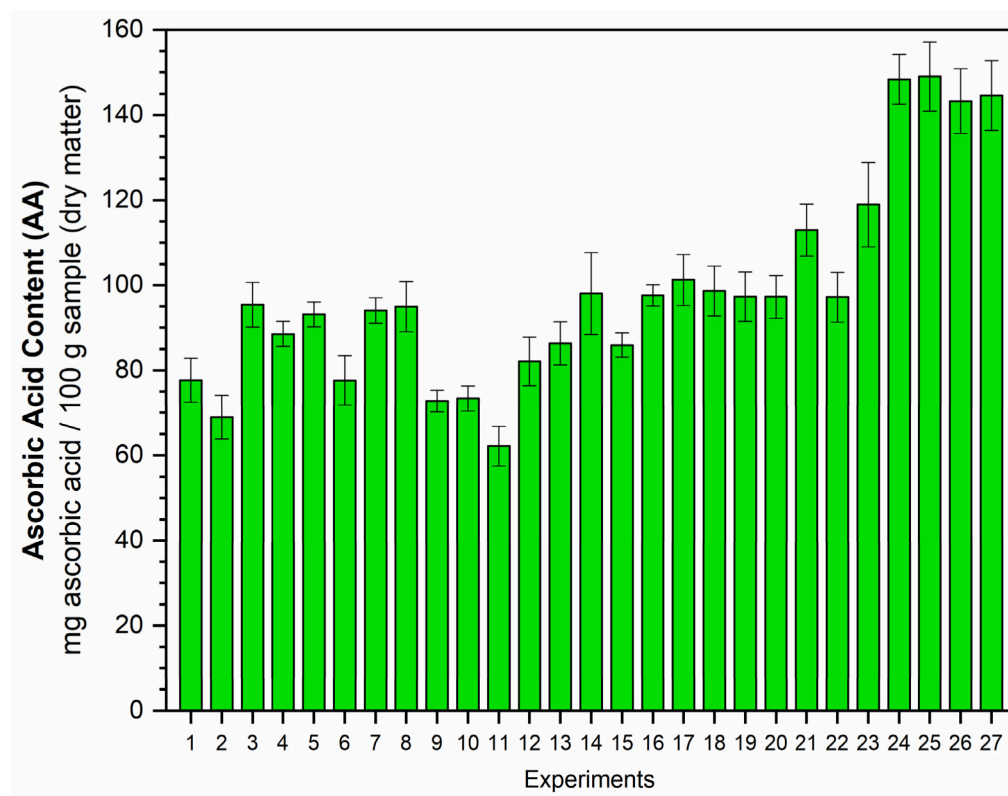


Figure 8. Ascorbic acid content (AA) results.

Through regression analysis of the experimental data, Equation (9) ($R^2 = 0.8632$) was obtained, indicating that all evaluated variables influenced ascorbic acid content. The model further confirms that AA retention is strongly dependent on processing conditions, reinforcing its sensitivity to spray drying parameters, particularly those associated with thermal exposure and mass transfer dynamics.

$$AA = 140.34 - 12.82 \cdot x_1^2 - 16.57 \cdot x_2 - 42.15 \cdot x_2^2 - 19.12 \cdot x_3 - 38.42 \cdot x_3^2 + 14.06 \cdot x_4 - 21.46x_4^2 \quad (9)$$

In Figure 9, the response surface analysis shows that intermediate experimental conditions resulted in the highest ascorbic acid (AA) retention. Specifically, temperatures (T) between 130 and 150 °C combined with drying air flow rates between 1.5 and 1.7 m³/min favored higher AA contents, a trend consistent with the results observed in Figure 8, where Experiments 25, 26, and 27 (central points of the experimental design) exhibited the highest AA values. This behavior suggests that AA retention is strongly dependent on a balance between thermal load and drying kinetics, where moderate process conditions may reduce excessive thermal exposure while maintaining efficient moisture removal [76,77].

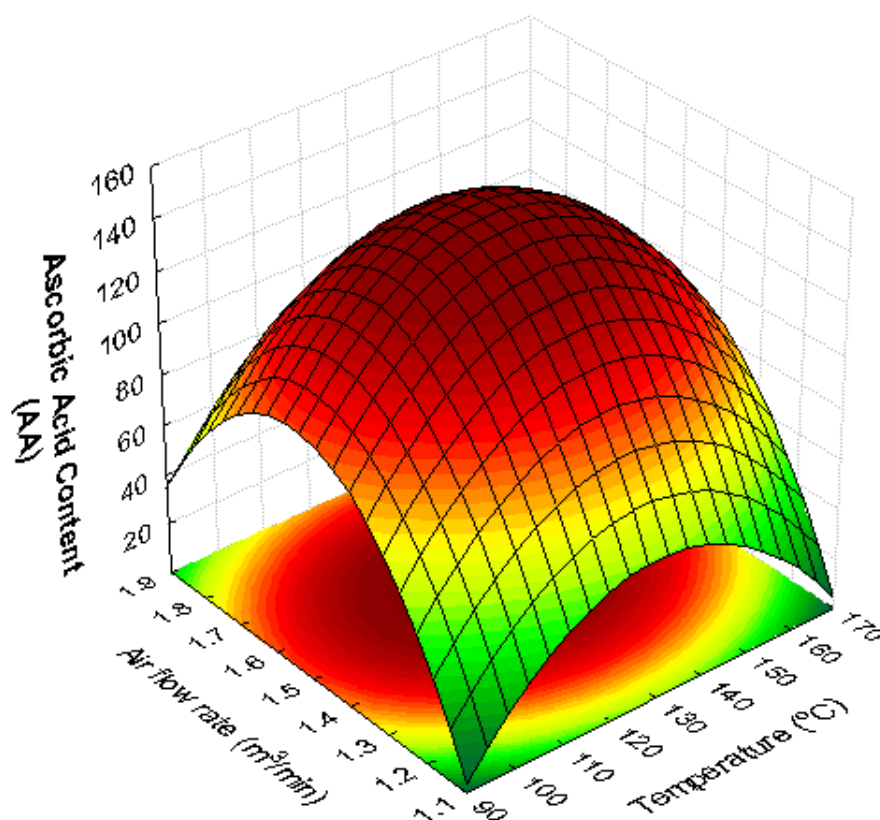


Figure 9. Ascorbic acid content (AA) response surface: air flow rate (AF) × temperature (T).

3.2.4. Betalain Content (BE)

Betalains are water-soluble natural pigments responsible for the red–purple (betacyanins) and yellow–orange (betaxanthins) coloration in plant tissues [14,78]. In addition to their role as natural colorants, these compounds have gained considerable scientific interest due to their significant antioxidant capacity, including free radical scavenging activity and the ability to reduce oxidative stress, making them promising alternatives to synthetic food dyes [11]. In red pitaya, betalains are responsible for the characteristic red–purple coloration of the pulp and peel, contributing both to the visual quality and functional value of the fruit [79,80].

The betalain content (BE) results obtained for each experiment condition are presented in Figure 10. A significant variation in the levels of this bioactive compound was observed

in the final product, highlighting the influence of spray drying parameters on betalain retention. The betalain content ranged from 21.31 to 52.79 mg per 100 g sample on a dry matter, whereas the BE content in the fresh pitaya was 83.45 ± 4.17 mg of betalain per 100 g of sample on a dry matter, indicating a reduction in pigment content after processing.

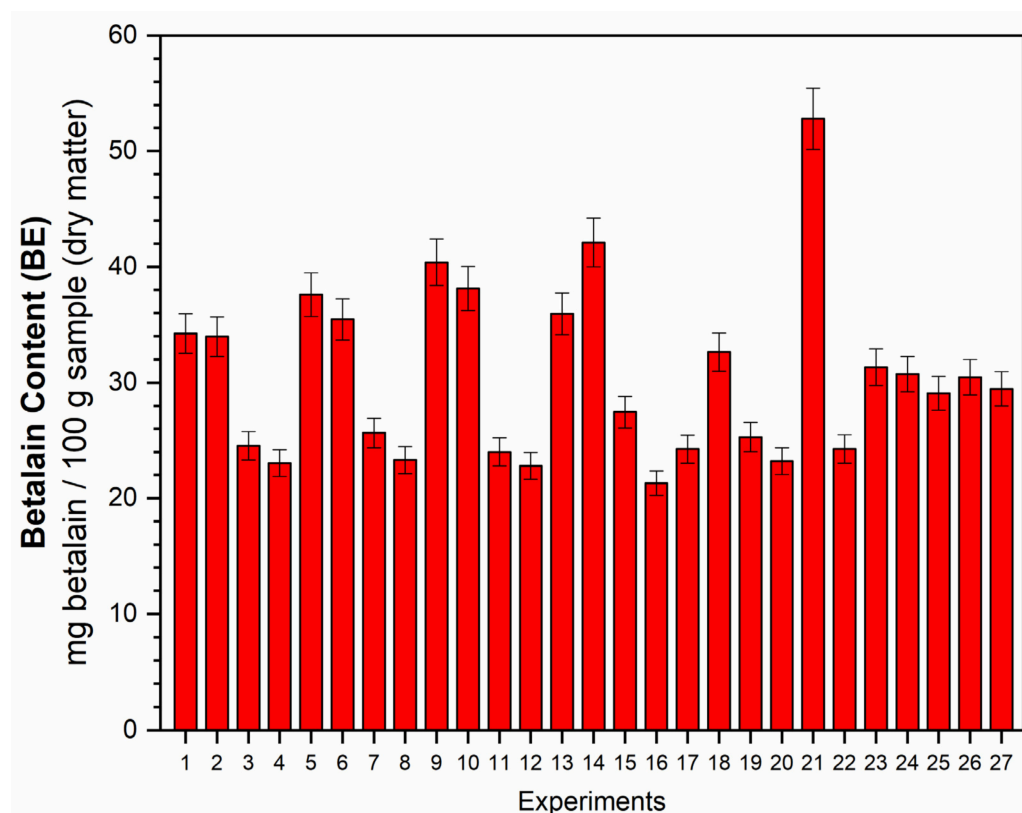


Figure 10. Betalain content (BE) results.

Regression analysis of the experimental data yielded Equation (10) ($R^2 = 0.9558$), indicating that all four variables significantly influenced betalain content. Consistent with the trends observed for other bioactive compounds, maltodextrin (x_3) exhibited the most pronounced negative effect on betalain retention, which can be associated with dilution effects and changes in the solid matrix composition. In contrast, temperature exerts a positive linear effect on betalain content, suggesting that within the evaluated range, higher drying temperatures contributed to improved pigment retention. This behavior may be associated with rapid moisture removal at these conditions, which reduces the exposure time of betalains to oxidative degradation during processing [81].

$$BE = 29.74 + 1.30x_1 - 1.36x_2^2 - 6.78x_3 + 2.21x_3^2 - 1.02x_1x_3 - 0.79x_3x_4 \quad (10)$$

The response surface shown in Figure 11 indicates that increasing the drying temperature above 150°C , combined with intermediate drying air flow rates (around $1.5\text{ m}^3/\text{min}$) resulted in higher betalain concentrations in the final powder, as exemplified by Experiment 14, which reached 42.12 mg betalain per 100 g sample on dry basis. In contrast to the trends observed for TPC, TFC, and AA, where increasing temperature generally resulted in compound degradation, the betalain exhibited an opposite behavior, with higher temperatures leading to improved retention under certain conditions. Research by Moreira et al. [77] and Lim et al. [80] have suggested that this distinct behavior may be related to structural changes occurring in betalains when exposed to thermal processing conditions. Under heat exposure, these pigments may undergo structural modifications in an attempt to reach

more stable configurations, which may allow partial regeneration and recovery some of their original properties after processing.

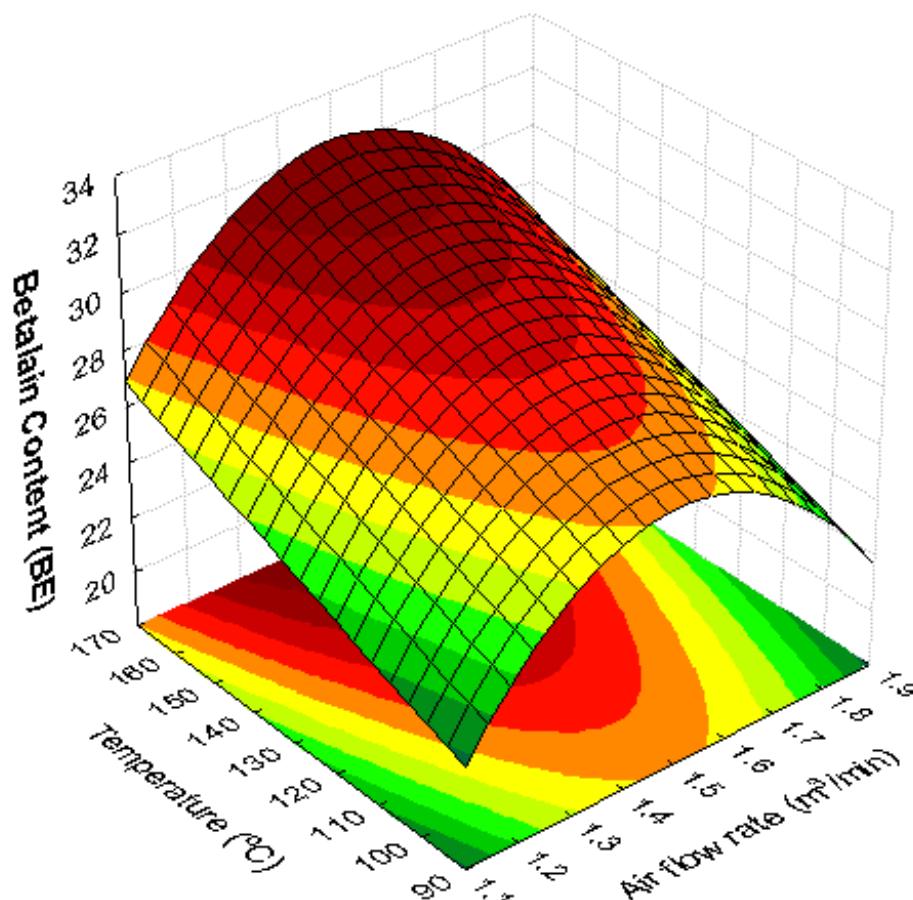


Figure 11. Betalain content (BE) response surface: air flow rate (AF) $\times$ temperature (T).

Overall, the bioactive content results show that the retention of phenolic compounds, flavonoids, ascorbic acid, and betalains is strongly influenced by spray drying conditions, with each bioactive compound exhibiting distinct sensitivity to the evaluated process variables. These differences indicate that no single set of operating conditions simultaneously maximizes all responses. In this context, the use of the whole pitaya fruit provides a broad source of bioactive compounds but requires careful adjustment of processing parameters to balance their retention, while also enhancing the utilization of the entire fruit biomass, including fractions that are typically discarded, thereby improving overall resource efficiency in the valorization process.

3.3. Multi-Response Optimization

The experimental results were used to identify the optimal operating conditions for producing pitaya powder with satisfactory yield and bioactive compound retention. Drying yield (DY), along with total phenolic (TPC), total flavonoid (TFC), ascorbic acid (AA), and betalain (BE) contents, were simultaneously considered as response variables in the desirability function analysis (Figure 12).

The optimal conditions were identified as a temperature (T) of 132.7 °C (+0.1333 in coded values—Table 1), air flow rate (AF) of 1.51 m³/min (+0.06667), maltodextrin concentration (M) of 9.0% (−1), and feed flow rate (FF) of 0.55 L/h (−1). Under these conditions, the regression models (Equations (5) and (7)–(10)) predicted a drying yield (DY) of 35.99%, along with total phenolic content (TPC) of 101.98 mg gallic acid/100 g, total

flavonoid content (TFC) of 1.93 mg rutin/100 g, ascorbic acid content (AA) of 112.12 mg/100 g, and betalain content (BE) of 39.82 mg/100 g (dry basis).

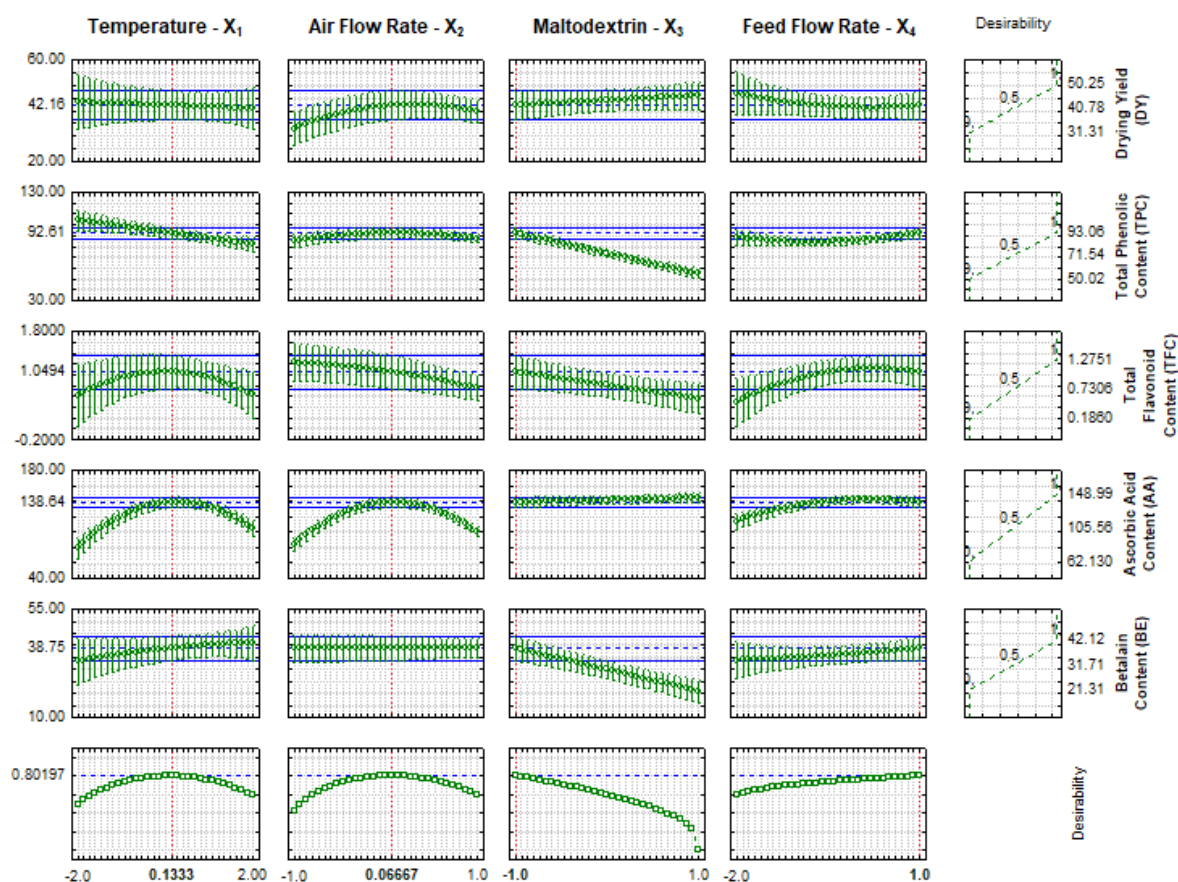


Figure 12. Desirability functions for drying yield (DY), total phenolic (TPC), total flavonoid (TFC), ascorbic acid (AA) and betalain content (BE).

It was observed that, under the optimal conditions, the predicted values for drying yield and bioactive compounds were lower than the maximum experimental values reported in Table 2 and Figures 4, 6, 8 and 10. This behavior is expected in multi-response optimization approaches, since the desirability function identifies a compromise solution rather than maximizing individual responses independently. However, the optimized conditions still provided balanced performance across all evaluated responses. These findings indicate that the selected conditions effectively integrate process efficiency and product quality, supporting their applicability for the production of spray-dried pitaya powder.

3.4. Color

In addition to bioactive compound content analysis, color was evaluated in the spray-dried powders, as a key quality attribute closely related to consumer acceptance and as an indirect indicator of pigment stability during processing [81,82]. The instrumental color parameters of the obtained powders are presented in Table 3.

The fresh pitaya presented an L* value (brightness) of 21.90, whereas the spray-dried powders showed lower values ranging from 12.29 to 14.53, indicating a reduction in lightness after processing. This behavior is likely associated with pigment concentration and redistribution during spray drying, as well as the incorporation of maltodextrin (white low-color carrier agent), which modifies the optical properties of the powder matrix. In addition, the observed differences among powder samples suggest that processing

conditions had influence on color lightness, possibly related to variations in pigment stability during different operational conditions [79,80].

Table 3. Results for the color variables of spray-dried pitaya powders.

Exp.	L*	a*	b*	C*	H°	ΔE
1	12.87	5.68	1.15	14.07	11.45	12.85
2	12.53	5.65	1.08	13.74	10.82	13.12
3	13.67	6.01	1.03	14.93	9.72	12.07
4	13.57	5.56	1.05	14.66	10.69	12.46
5	13.84	6.02	1.02	15.09	9.62	11.95
6	13.13	5.55	0.93	14.25	9.51	12.78
7	13.92	5.60	1.02	15.00	10.32	12.21
8	13.96	4.25	0.98	14.56	12.98	13.25
9	13.51	5.63	1.05	14.64	10.56	12.45
10	13.82	6.42	1.21	15.24	10.67	11.65
11	13.10	5.49	0.86	14.20	8.90	12.85
12	13.76	5.56	0.96	14.84	9.80	12.35
13	12.89	5.37	0.64	13.96	6.80	13.10
14	12.30	6.01	1.04	13.69	9.82	13.04
15	13.30	5.92	0.93	14.56	8.93	12.40
16	13.46	5.66	0.91	14.60	9.13	12.48
17	13.83	5.44	1.16	14.86	12.04	12.37
18	13.51	5.77	0.87	14.69	8.57	12.37
19	13.57	5.74	1.04	14.73	10.27	12.33
20	13.90	5.87	0.98	15.09	9.48	12.02
21	12.29	5.58	0.98	13.50	9.96	13.35
22	14.53	5.44	0.99	15.51	10.31	11.94
23	13.28	5.68	0.99	14.44	9.89	12.58
24	13.34	6.11	1.19	14.67	11.02	12.21
25	12.97	5.83	1.12	14.22	10.87	12.68
26	12.81	5.77	1.14	14.05	11.18	12.83
27	12.93	5.59	1.11	14.09	11.23	12.87

The a^* parameter of the spray-dried powders ranged from 4.25 to 6.42, indicating differences in red color intensity across the experimental conditions. Compared to the fresh pitaya, which presented an a^* value of 14.77, a marked reduction was observed, reflecting the loss of the characteristic red coloration after the spray drying process. This behavior can be attributed to the partial degradation of red pigments during thermal processing, combined with dilution and matrix effects associated with maltodextrin incorporation, which modifies the overall color expression of the powder [79,80].

A similar trend was observed for the b^* parameter, which ranged from 0.64 to 1.21, indicating variations in the yellow component among the experimental conditions. Fresh pitaya exhibited a higher b^* value (2.12), and the reduction observed in the powders suggests a decrease in yellow color intensity after drying, following the same trend observed for the a^* parameter.

To provide a better discussion of color changes, the chroma (C^*) and hue angle (H°) were statistically evaluated, allowing a deeper understanding of the impact of the drying experimental conditions on powder color stability.

Chroma (C^*) values of the spray-dried powders ranged from 13.50 to 15.51, substantially lower than that of fresh pitaya (26.42). This reduction indicates a reduction in color saturation after drying, consistent with the reductions verified in the a^* and b^* parameters. Lower chroma values reflect a loss of color intensity, resulting in a transition from the characteristic intense red-purple coloration of the fresh fruit to lighter pink tones in

the powders (as can be seen in Figure 2). This behavior may be associated with partial pigment degradation of pigments during spray drying, as well as matrix effects induced by maltodextrin addition, which influence the optical properties of the powder, as previously reported. Similar findings were reported by Lee, Wu, and Siow [39], who observed a reduction in color saturation, with the samples shifting from an intense red color to lighter pink tones with slight yellowish hues after pitaya spray drying.

Through regression analysis of the experimental data, Equation (11) ($R^2 = 0.8234$) was obtained for the C^* parameter. All independent variables showed significant effects on C^* , highlighting the multifactorial nature of color formation in spray-dried pitaya powders. Temperature (x_1) played a relevant role, not only influencing C^* directly but also exhibiting significant interaction effects with the other variables, indicating that heat transfer conditions modulate the combined effects of mass transfer and matrix composition. In particular, the interaction between temperature and maltodextrin indicates a balance between pigment stabilization within the carrier matrix and dilution-related effects, while interactions with air flow and feed rate reflect coupled heat and mass transfer phenomena during droplet drying [83–85]. These results emphasize that color saturation is governed by interdependent process variables rather than isolated effects, reinforcing the importance of considering interaction terms in spray-drying optimization models.

$$C^* = 13.95 + 0.12x_1 + 0.18x_1^2 + 0.21x_2^2 + 0.25x_3 + 0.12x_4 - 0.13x_1x_2 - 0.27x_1x_3 + 0.20x_1x_4, \quad (11)$$

For the H° parameter, both the fresh sample ($H^\circ = 8.17$) and the spray-dried powders, with values ranging from 6.80 to 12.98 (Table 3) exhibited hue angles close to 0° , indicating a dominant red coloration [58,59]. Through regression analysis, Equation (12) ($R^2 = 0.8428$) was obtained, revealing the combined influence of process variables and their interactions. Temperature (x_1) showed a significant negative effect on H° , indicating that increasing thermal load promoted a shift in hue and a reduction in color stability. Similarly, air flow rate (x_2) exhibited both a negative linear effect and a significant quadratic term, suggesting a non-linear relationship with hue, likely associated with the balance between drying kinetics and exposure to oxidative conditions during particle formation. In contrast, feed flow rate (x_4) presented a positive effect, suggesting a tendency to preserve or slightly increase H° values, possibly due to reduced thermal exposure and shorter residence time within the drying chamber [84,85].

$$H^\circ = 10.42 - 0.82x_1 - 0.20x_2 - 0.19x_2^2 + 0.48x_4 - 0.45x_1x_2 - 0.49x_2x_3 + 0.41x_2x_4, \quad (12)$$

In addition, significant interactions were observed between temperature and air flow rate (x_1x_2), air flow rate and maltodextrin concentration (x_2x_3), and air flow rate and feed flow rate (x_2x_4). These findings indicate that H° behavior is influenced by interaction process variables, rather than by individual process variables alone, reflecting the combined effects of heat and mass transfer phenomena during droplet drying, where thermal and fluid dynamic conditions act simultaneously on pigment stability and color development.

The response surfaces presented in Figure 13 illustrate the behavior of C^* (Figure 13a) and H° (Figure 13b) as function of the evaluated process variables. The response surface presented in Figure 13a indicates that higher C^* values were achieved under extreme conditions, particularly at low and high temperatures (T) combined with high and low maltodextrin concentrations (M), respectively. According to Gharsallaoui et al. [83] and Vehring [85], rapid water removal at appropriate thermal conditions promotes early glass transition and encapsulation of bioactive pigments, reducing molecular mobility and limiting chromophore degradation. However, insufficient carrier concentration may also reduce matrix protection, leading to heterogeneous color retention depending on process severity.

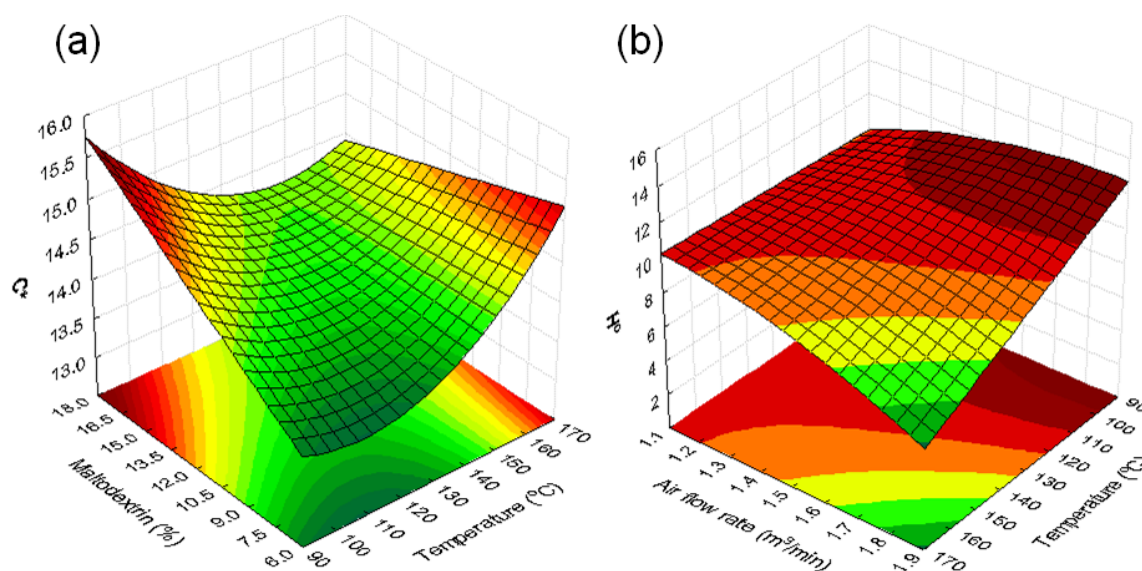


Figure 13. Response surfaces: (a) C^* as function of maltodextrin concentration (M) $\times$ temperature (T) and (b) H° as a function of as function of air flow rate (AF) $\times$ temperature (T).

In contrast, Figure 13b shows that lower hue angle (H°) values were obtained at higher temperatures combined with higher feed flow rates. This behavior indicates a shift toward a more reddish tonal profile under conditions that enhance drying efficiency and reduced residence time within the drying chamber. As described by Cal and Sollohub [84], increased inlet temperature combined with higher atomization throughput can intensify heat and mass transfer rates, shortening droplet exposure to oxidative and thermal degradation. Consequently, pigment transformation pathways associated with browning or yellowing are minimized, maintaining hue values closer to the original red chromatic profile of the fresh material.

The total color difference (ΔE) is used to classify the perceptibility of color differences between samples. In this study, ΔE values ranged from 11.65 and 13.35, indicating that all spray-dried powders exhibited noticeable color differences compared to the fresh material. These results confirm that spray drying significantly alters the overall color attributes of red pitaya. However, the relatively narrow ΔE range suggests that the process conditions led to a certain level of consistency in the magnitude of color change among the produced powders.

Although the observed ΔE values indicate noticeable color differences compared to fresh pitaya, the magnitude of the color shift does not necessarily represent a barrier for application in food systems, particularly in powdered formulations where color is reconstituted during use or incorporated into complex matrices. However, for applications that requiring high color fidelity, such as natural colorant ingredients, mitigation strategies may be considered. These include the use of enhanced encapsulation systems, blending with complementary natural pigments, or formulation-based color adjustment to improve visual stability and reduce pigment degradation effects during processing and storage [86].

As expected, the observed changes in color parameters provide evidence of the stability and transformation of naturally occurring pigments, which are inherently associated with both the pulp and peel fractions of pitaya [6,15]. Considering that whole fruit was used in this study, the resulting color attributes are influenced by the combined contribution of pigment-rich fractions and the effects of spray drying conditions. Although reductions in color intensity and saturation were observed after spray drying, the relatively consistent H° values and narrow ΔE range suggest that the overall color profile was maintained within a similar chromatic region across the evaluated conditions. These results indicate that spray

drying preserved the main visual characteristics of the raw material to a certain extent, despite the expected changes induced by processing conditions.

4. Conclusions

This study demonstrated that red pitaya (*Hylocereus costaricensis*) proved to be rich in bioactive compounds, including phenolics, flavonoids, ascorbic acid, and betalains, highlighting its potential as a functional ingredient in food systems. The characterization of the whole fruit revealed higher levels of these compounds compared to studies based only on the pulp, emphasizing the importance of including peel and seeds as functional fractions. Spray drying of whole pitaya (pulp, peel, and seeds) proved to be an effective strategy for producing a stable powder, contributing to improved fruit utilization and supporting more sustainable processing through the valorization of typically underused fractions.

All evaluated conditions produced powders with low moisture content (0.95–4.66%) and reduced water activity (0.111–0.335), ensuring microbiological stability and shelf-life extension. These results confirm spray drying as an efficient preservation strategy for highly perishable fruits such as pitaya and support its applicability for producing stable, value-added ingredients. Maltodextrin was essential for process feasibility, although its concentration must be controlled to balance drying performance and product quality. Drying yield (DY) was governed by the combined effect of the evaluated variables, with intermediate conditions generally providing improved performance.

Process conditions significantly influenced the retention of bioactive compounds, although each class exhibited distinct sensitivity to the evaluated variables. Overall, moderate processing conditions provided a balanced performance among responses, reflecting the trade-off between thermal exposure, drying kinetics, and matrix effects inherent to spray drying. These results indicate that no single operating condition simultaneously maximizes all evaluated responses.

In this context, the multi-response desirability approach was applied to integrate drying yield and bioactive compound contents into a single optimization criterion. The optimized conditions ($T = 132.7\text{ }^{\circ}\text{C}$, $AF = 1.51\text{ m}^3/\text{min}$, $M = 9.0\%$, and $FF = 0.55\text{ L/h}$) resulted in a drying yield of 35.99%, together with TPC of 101.98 mg gallic acid/100 g, TFC of 1.93 mg rutin/100 g, AA of 112.12 mg/100 g, and BE of 39.82 mg/100 g (dry basis). These results demonstrate the feasibility of jointly optimizing process efficiency and product quality through an integrated multi-response strategy and may serve as a practical reference for obtaining spray-dried whole pitaya powder with balanced process efficiency and product quality.

Color analysis confirmed that spray drying induced changes in all evaluated parameters (L^* , a^* , b^* , C^* , H° , and ΔE), primarily driven by processing conditions and the presence of maltodextrin, as well as pigment degradation during thermal exposure. Compared to fresh pitaya, the powders exhibited lower L^* , a^* , and b^* values, indicating a general reduction in lightness and color intensity. Consequently, chroma (C^*) decreased, reflecting a loss of color saturation and a shift toward lighter pink tones. The hue angle (H°) showed only minor variations relative to the fresh sample, indicating partial preservation of red chromatic characteristics despite processing. ΔE values indicated noticeable color differences between fresh and spray-dried samples, confirming that spray drying significantly altered the overall color attributes of pitaya, while still maintaining a consistent red-based color profile across all conditions.

Overall, the results demonstrate the effectiveness of spray drying in producing stable pitaya powders with preserved physicochemical and functional properties. The process enables the conversion of a highly perishable fruit into a multifunctional ingredient with potential use as a natural colorant and source of bioactive compounds. However, the results

also show that product quality is strongly dependent on operating conditions and their interactions, highlighting the need for process optimization to achieve a balance between drying performance, bioactive compound retention, and color stability.

The use of the whole fruit, combined with optimized drying conditions, represented a relevant strategy for improving raw material utilization and generating value-added products from underexploited fractions, with direct implications for resource efficiency, as it allows the full valorization of the fruit biomass and reduces the generation of processing waste by incorporating typically discarded fractions such as peel and seeds into the final product. Future work may focus on process scale-up and on the application of the obtained powders in food, pharmaceutical, and nutraceutical systems.

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