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Valorization of dragon fruit (*Selenicereus undatus* L.) cladodes as source of functional flour: effect of drying conditions and maturity stage

Valorización de los cladodios de pitahaya (*Selenicereus undatus* L.) como fuente de harina funcional: efecto de las condiciones de secado y la etapa de madurez

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Abstract

Pitahaya cladodes have been already identified as material with some interesting biological activities. However, it remains an underutilized waste from periodic pruning. This study investigated the production of functional flours from cladodes of pitahaya (*Selenicereus undatus* L.), evaluating the effect of maturity stage (tender and mature) and convective drying temperatures (30, 45, and 60 °C). Proximate composition analysis showed that tender cladodes (TC) have a significantly higher amount of crude fiber on dry basis (36.0 ± 3.44 %) compared to mature cladodes (MC) (21.49 ± 2.69 %). Drying kinetics were characterized by a predominantly falling-rate period, with experimental data showing the best fit for the Page model for drying at 60 and 45 °C and Midilli model for 30°C (R^2 > 0.99), indicating that temperature was the main driver of mass transfer (effective diffusivity range 1.636 - 7.160 10^{-8} m^2/s) regardless of maturity stage (activation energy of 40.75 and 38.42 kJ/mol, for MC and TC respectively). The techno-functional properties of flours were significantly influenced ($p<0.05$) by the processing conditions. Water-holding capacity (WHC) reached maximum value at 60 °C (760.00 ± 11.70 %) in the MC flour, while solubility decreased with increasing temperature. Colorimetric analysis showed that higher temperatures and advanced maturity led to a reduction in lightness (L*) and an increase in chroma (C*). These technical results provide the foundation for closing the production loops of pitahaya cultivation and reducing environmental impac. The conversion of pruning waste into value-added resources supports the economic and environmental sustainability of producing regions.

Keywords: *Hylocereus undatus*, circular bioeconomy, mathematical modeling, functional flours, agro-industrial waste.

Resumen

Los cladodios de pitahaya ya han sido identificados como un material con actividades biológicas interesantes; sin embargo, siguen siendo un residuo subutilizado proveniente de las podas periódicas. Este estudio investigó la producción de harinas funcionales a partir de cladodios de pitahaya (*Selenicereus undatus* L.), evaluando el efecto del estado de madurez (tierno y maduro) y de las temperaturas de secado (30, 45 y 60 °C). El análisis de composición proximal mostró que los cladodios tiernos (CT) presentan una cantidad significativamente mayor de fibra cruda en base seca (36.0 ± 3.44 %) en comparación con los maduros (CM) (21.49 ± 2.69 %). La cinética de secado se caracterizó por un periodo de velocidad decreciente predominante; los datos experimentales mostraron el mejor ajuste al modelo de Page para el secado a 60 y 45 °C, y al modelo de Midilli para 30 °C (R^2 > 0.99). La temperatura fue el factor determinante de la transferencia de masa (rango de difusividad efectiva de 1.636 a 7.160 $\times 10^{-8}$ m^2/s), independientemente del estado de madurez (energía de activación de 40.75 y 38.42 kJ/mol para CM y CT, respectivamente). Las propiedades tecnofuncionales de las harinas se vieron influidas significativamente ($p < 0.05$) por las condiciones de procesamiento. La capacidad de retención de agua alcanzó su valor máximo a 60 °C (760.00 ± 11.70 %) en la harina de CM, mientras que la solubilidad disminuyó al aumentar la temperatura. El análisis colorimétrico reveló que las temperaturas más altas y un mayor grado de madurez provocaron una reducción de la luminosidad (L*) y un aumento del croma (C*). Estos resultados proporcionan la base para cerrar los ciclos de producción del cultivo de pitahaya y reducir el impacto ambiental. La conversión de los residuos de poda en recursos de mayor valor agregado apoya la sostenibilidad económica y ambiental de las regiones productoras.

Palabras clave: *Hylocereus undatus*, bioeconomía circular, modelado matemático, harinas funcionales, residuos agroindustriales.

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1 Introduction

The comprehensive use of agro-industrial resources represents both a fundamental challenge and a significant opportunity within the framework of the circular bioeconomy, particularly in regions of Mexico, where the cultivation of cacti holds profound economic, social, and cultural importance. Among these species, pitahaya (*Selenicereus undatus* L.), internationally recognized as dragon fruit, has garnered increasing interest. Recent advances in taxonomy have reported that there is no clear separation between the genera *Selenicereus and Hylocereus.* Then both genera were merged under the name *Selenicereus* (Korotkova *et al*., 2017).

In 2024, 2,537.78 ha of pitahaya were planted in Mexico (SIAP, 2026), of these, 148.45 ha were planted in the state of Puebla (primarily in the Mixteca Poblana region) where its cultivation serves as a key economic source for marginalized communities. In addition to fruit consumption, the cladodes also have potential for valorization. Usually, pruning is done two or three times a year. In traditional plantations in Mixteca Poblana 800 kg cladodes per ha. The biggest pruning of the crops takes place in January. The next pruning happens in mid-March, before flowering. The third one is done in November (personal communication). Under extensive conditions, each hectare of pitaya farmland can generate around 60 tons of wasted cladodes (Nurul & Asmah, 2014). This biomass volume creates serious environmental problems (Reyes-García *et al*., 2024).

Furthermore, it is rich in dietary fiber, mucilage, and compounds with functional and antioxidant properties. From a nutritional and technological point of view, these vegetative organs are a promising raw material for the food industry (Som *et al*., 2019). Studies conducted on other cacti indicate that these byproducts contain significant levels of polyphenols and vitamins, which can be incorporated into food formulations to improve consumer health (Nabil *et al*., 2020; Rössel-Kipping *et al*., 2022; Reyes-García *et al*., 2024).

The current technologies available allow the preparation of a wide range of products from young or mature cladodes (fresh-cut, pickled, brined, etc.). A method of a preservation process used for many years is dehydration, which is based on reducing the water content. However, the processing of cladodes presents considerable technical challenges due to their high initial moisture content (83-91%). Convective drying is one of the most widely employed unit operations for the preservation of these matrices. It effectively reduces water activity and arrests microbial and enzymatic degradation (Díaz-Ayala *et al*., 2015). In this sense, the modeling of the drying process is indispensable for equipment design, industrial process optimization, energy integration, and the implementation of automated dryer control systems. Semi-empirical models consist of equations derived from the simplification of physical laws (primarily Fick's second law of diffusion). They are subsequently fitted using experimental parameters to describe moisture loss during dehydration. These models are widely preferred in food engineering because they require fewer computational assumptions than purely theoretical models. At the same time, offer significantly higher precision than purely empirical ones (Erbay & Icier, 2010).

Drying is the most widely utilized unit operation for converting cladodes into stable flours However, the operating conditions significantly influence the functionality of the resulting matrix (Contreras-Padilla *et al*., 2012). It has been demonstrated that critical factors, such as air temperature and the maturity stage of the tissue, directly influence dehydration kinetics and the final physicochemical properties of the product. Inadequate drying conditions can lead to undesirable changes in sensory quality.

Techno-functional properties are defined as the fundamental physicochemical characteristics that reflect the complex interaction among the composition, structure, and molecular conformation of ingredients (De Angelis *et al*., 2024). These properties serve as a direct indicator of the material's potential to be incorporated into food matrices as additives or functional ingredients.

In the case of *Opuntia ficus-indica*, the techno-functional properties of its cladodes have driven their industrial utilization as a source of bioactive substances and supplementary ingredients (Nabil *et al*., 2020; Sánchez-Gutiérrez *et al*., 2022; Aparicio-Ortuño *et al*., 2024). Authors such as Contreras-Padilla *et al*. (2012) and Beyá-Marshall *et al*. (2022) have demonstrated that the quality of the resulting powders depends on both the drying temperature and the maturity stage of the cladode, the latter determining the initial fiber profile and mucilage composition. During thermal processing, the extent of heat-induced changes is closely linked to this physiological maturity. Higher drying temperatures can lead to altered color parameters, the degradation of heat-sensitive compounds, and modifications to properties such as water absorption, oil absorption, and solubility. In contrast, younger cladodes tend to retain superior techno-functional characteristics due to their higher content of soluble fiber and mucilage (Nuñez-López *et al*., 2013; Boukid *et al*., 2015).

In this context, despite the abundance of pitahaya cladodes byproduct, to the best of our knowledge, there is a lack of scientific literature regarding the optimization of drying specifically for pitahaya cladodes oriented towards the production of functional flours. Therefore, the objective of this study was to evaluate the combined effect of convective drying temperature (30 – 60 °C) and cladode maturity stage on (i) drying kinetics and mass transfer parameters, (ii) effective moisture diffusivity and activation energy, and (iii) the techno-functional properties of pitahaya (*S. undatus*) cladode flours, with the aim of supporting their valorization as functional food ingredients.

2 Materials and methods

2.1 Chemicals

Analytical grade reagents were used, including hexane, chloroform, dichloromethane, acetone, methanol, ethyl acetate, ethanol, acetic acid, hydrochloric acid, formic acid, sulfuric acid, and ethyl ether purchased by Sigma Aldrich.

2.2 Pitahaya cladodes

Fresh pitahaya (*S. undatus*) cladodes were harvested from a plot located in Xochitlán Todos Santos, Puebla, Mexico (18°42.755' N, 97°48.191' W) during January – February 2022. Samples were classified into two maturity stages, tender cladodes (TC) (40 to 50 days of regrowth, average length 39.8 ± 5.5 cm) and mature cladodes (MC) (> 90 days of regrowth, average length 79.3 ± 19.9 cm). The material was washed and disinfected with a Citrosan® solution, and excess moisture was removed at room temperature prior to cutting the samples into 3.5 ± 0.2 mm thick transverse slices.

2.3 Proximal analysis

The two maturity stages of fresh pitahaya cladodes were analyzed. Moisture content was determined according to the AOAC official method 905.10 (AOAC, 2018). For chemical characterization, the following standardized protocols were employed: total nitrogen was measured via the micro-Kjeldahl method, using a conversion factor of 6.25 to calculate crude protein (Badia-Olmos *et al*., 2023). Crude fiber was determined by sequential acid/alkaline digestion (AOAC, 2018), Meanwhile, the ether extract fraction was extracted using the Soxhlet method (AOAC 920.39) with petroleum ether as the solvent. Ash content was analyzed by incineration in a muffle furnace at 550 °C for 4 h (AOAC 942.05). Finally, total carbohydrates content was determined by difference according to Fikiru *et al*. (2017).

2.4 Drying kinetics

The drying kinetics were evaluated utilizing a tray dryer (Hidrosam, model Didactic, Puebla, Mexico). Air velocity was maintained at 1 m/s and systematically monitored with a digital vane anemometer (UNI-T, model UT363S, Hong Kong, China). The evaluated drying temperatures were 30, 45, and 60 °C. The cladode slices (3.5 ± 0.2 mm) were placed in a single layer, with weight loss monitored at regular intervals until equilibrium was achieved. The parameters were selected based on previous studies on similar matrices (Touil *et al*. 2014; Medina *et al*., 2023). All weights were determined using an analytical balance (Velab, model VE-204, CDMX, Mexico). The drying procedure was finished when the difference between successive measurements was less than 0.0005g. Each drying experiment was conducted in triplicate. Experimental data were converted into the dimensionless moisture ratio (Ψ, kg of water/kg of dry solids) according to Equation 1.

$$\Psi = \frac{X - X_e}{X_0 - X_e} \tag{1}$$

Where X represents the moisture content at time (t), X_0 is the initial moisture content, and X_e is the equilibrium moisture content. To obtain equilibrium moisture, the samples were subsequently dried at 60 °C and 60 kPa in a vacuum oven until a constant mass was achieved, according to the AOAC official method 934.01 (AOAC, 2018) (Díaz-Ayala *et al*., 2015; Olguín-Rojas *et al*., 2019).

2.5 Estimation of effective diffusivity coefficients

Mass transfer during the drying of cacti is governed by Fick's law of unsteady-state diffusion (Medina-Torres, 2008). Since the constant rate period is typically absent in these plant matrices, the process is controlled by the internal diffusion of water from the core to the surface during the falling rate period (Díaz-Ayala *et al*., 2015). To calculate the effective diffusivity of moisture (D), the analytical solution of Fick's second law for infinite flat plate geometry (Equation 2) was used, with l as half the characteristic thickness.

$$\Psi = \frac{8^2}{\pi^4} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left(-\frac{(2n-1)^2 \pi^2 D t}{4l^2}\right) \tag{2}$$

Following the approach proposed by Olguín-Rojas *et al*. (2019), the D was estimated by fitting the linear portion of the semilogarithmic plot of Ψ against drying time to the simplified analytical solution for a flat plate (Equation 3). This ensures that the diffusivity is determined within the diffusion-controlled falling-rate period, thereby providing a physically consistent parameter.

$$\Psi = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 Dt}{4l^2}\right) \tag{3}$$

In the semilogarithmic plot of ψ versus time (Equation 4), the slope in the linear region corresponds to m, while a represents the intercept, as described in Equation 5.

$$\ln \Psi = \ln \frac{8}{\pi^2} - \frac{\pi^2 Dt}{4l^2} \tag{4}$$

$$\ln \Psi = a + mt \tag{5}$$

Where:

$$m = -\frac{\pi^2 D}{4l^2} \tag{6}$$

The 95% confidence interval for the diffusivities (the slopes, m) was calculated using the equation 7:

$$m_0 = m \pm t_{0.975(\nu)} \sqrt{s_m^2} \tag{7}$$

where m_0 represents the 95% confidence interval for slope calculated from the linear regression (m), s_m^2 is the estimated variance of the linear parameter, $t_{0.975(\nu)}$ is the value from the cumulative distribution of the t-student function for a 0.975 probability, ν represents the degrees of freedom (ν = n-2) and n is the number of experimental drying kinetics points.

The activation energy (Ea) was determined using the relationship between the effective diffusivity (D) and the drying air temperature (Equation 8).

$$\ln D = \ln D_0 - \frac{Ea}{R}\frac{1}{T} \tag{8}$$

For estimation of the effective diffusivity coefficients, plotting, and numerical fitting were performed using Microsoft Excel 365 software.

2.6 *Semi-empirical drying modeling*

The dimensionless moisture content (Ψ) was fitted to different thin-layer drying models commonly used in the literature (Erbay & Icier, 2010): Lewis (Equation 9), Page (Equation 10), Henderson and Pabis (Equation 11), Logarithmic (Equation 12), Midilli (Equation 13), and Two-term (Equation 14). Nonlinear regression was carried out using MATLAB (version 2025b, MathWorks, Natick, MA, USA) with the lsq curve fit function.

$$\Psi = e^{(-kt)} \tag{9}$$

$$\Psi = e^{(-kt^n)} \tag{10}$$

$$\Psi = a\, e^{(-kt)} \tag{11}$$

$$\Psi = a\, e^{(-kt^n)} + b \tag{12}$$

$$\Psi = a\, e^{(-kt^n)} + bt \tag{13}$$

$$\Psi = a\, e^{(-k_0 t)} + b\, e^{(-k_1 t)} \tag{14}$$

where k, n, a, b, k_0 and k_1 are empirical constants in models. The quality of fit was assessed using the coefficient of determination (R^2), the root means square error ($RMSE$), and the reduced chi-square (χ^2), defined, respectively, as equation 15 and 16:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{i,p} - MR_{i,e}\right)^2}{N}} \tag{15}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{i,p} - MR_{i,e}\right)^2}{N - n} \tag{16}$$

where $MR_{i,p}$ and $MR_{i,e}$ represent the predicted and experimental values of moisture ratio, respectively, N is the number of observations, and n the number of model parameters.

Additionally, two information criteria were employed to compare models while penalizing parameter complexity: the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) (Akaike, 1998; Schwarz, 1978). These criteria were calculated using the equations 17 and 18:

$$AIC = -2loglike + 2p \tag{17}$$

$$BIC = 2loglike + p\, ln(n) \tag{18}$$

where p, is the number of parameters, *loglike* is the logarithm of the likelihood function considering the estimates of the parameters and n number of observations. The most suitable model for each drying temperature was chosen by considering a high R^2 value, low values for $RMSE$ and χ^2, and the lowest AIC and BIC values. This approach ensured a robust and unbiased selection of the most suitable model to represent the drying behavior of pitahaya cladode slices. The models were fitted to the mean moisture ratio at each time point. All drying kinetics represent the mean of three independent replicates (n = 3).

2.7 *Determination of the properties of cladode flours*

Once dehydrated, the cladodes were ground using a shear mill (HC-150, VEVOR, China) and sieved through a 177μm mesh. The properties of cladode flours obtained at different drying temperatures and stages of maturation were determined in triplicate. The methodology used is briefly described below.

2.7.1 *FT-IR characterization*

The functional groups of tender cladode flours (TCF) and mature cladode flours (MCF) were determined by Fourier-transform infrared spectroscopy (FT-IR) using an FT-IR GX System spectrophotometer (PerkinElmer, Shelton, CT, USA) coupled to a DuraSample II ATR accessory. The spectra were an average of 16 scans from 3600 to 800 cm^{-1} at a resolution of 2 cm^{-1}. The spectra were recorded as absorbance spectra.

2.7.2 Color determination

The determination of the color parameters of the flour samples (5g) was carried out using CR 400 Konica Minolta, Tokio, Japan. A white reflective plate to calibrate the device (L*=87.1000, a*=0.3153, and b*=0.3215) was employed. Color was reported as the lightness (L*), redness/greenness (a*) and yellowness/blueness (b*) coordinates values. The analysis was carried out in triplicate. Subsequently, the values of chroma (C*) (Eq.19) and hue angle (h*) (Eq.20) were calculated according to Wrolstad & Smith. (2017), using the following equations:

$$C^* = (a^{*2} + b^{*2})^{1/2} \tag{19}$$

$$h^* = arcot\,(b^*/a^*) + 180^\circ \tag{20}$$

2.7.3 Solubility determination

The solubility was determined according to Vargas Rodríguez *et al*. (2018) with modifications. In short, 50 mg of cladodes flours were added to 6 mL of water, contained in graduated conical tubes and vortexed for 3 min. The volume was brought up to 12 mL. The tubes were shaken again and left for 30 min. Subsequently, were centrifuged at 3500 rpm at 25 °C for 15 min. From each sample, 6 mL of the supernatant were added to previously tared aluminum foil capsules and maintained for 3h at 105 °C for dry matter determination. Solubility was expressed as a percentage (%).

2.7.4 Water holding capacity (WHC)

The WHC was determined by gravimetric method, according to Acosta and Morales (2023) with modifications. Forty mg of flours, were added to Eppendorf tubes, containing 1.5 mL of water, vigorously vortexed, filled up to 3 mL, and shaken again. Dispersions were left to rest for 24 h to allow to reach equilibrium and then were centrifuged at 10,000 rpm for 15 min. The supernatant was separated by decantation, and the tubes were kept inverted for 30 min at room temperature, weighing the precipitate with the retained water. The WHC was expressed as a percentage (%) of the mass of water retained.

2.8 Statistical analysis

The experiment was conducted using a completely randomized asymmetric 3 × 2 factorial design (drying air temperatures- 30, 45 and 60 °C, and two phenological maturity stages-TC and MC) in triplicate. All data were subjected to analysis of variance (ANOVA). Means were compared using Tukey's test (p≤ 0.05). Analyses were performed using Minitab software (version 16, State College, PA, USA).

3 Results and discussion

3.1 Proximal analysis of pitahaya cladodes

Tender (TC) and mature (MC) cladodes significantly differed (p<0.05) in moisture, ash, total carbohydrates, crude fiber, protein and fat contents (Table 1). Higher moisture, crude fiber and protein contents but lower total carbohydrate level were exhibited by TC in comparison with MC. Reviewing chemical, structural and the biological properties of the nopal cladodes, Perucini-Avendaño *et al*. (2021) reported values of total carbohydrates (38.0 to 61.40 %), crude fiber (5.97 to 55.05 %), fat (0.1 to 2.16 %), protein (6.7 to 11.73 %) and ash (14.4 to 23.05 %). Analyzed pitahaya cladodes showed results included in these ranges for crude fiber (%) and fat (%). Specifically, crude fiber content mainly in TC exceeds results usually reported for principal traditional cereals such as rice (*Oryza sativa* L.) (11.27 %), oats (*Avena sativa* L.) (13.19 %), as well as legumes like soybean (*Glycine max* (L.) Merr.) (7.37 %) (González-Obregón, 2002). This high content of fiber indicates that it could be an interesting source for human diets and could be used in foods, cosmetics and pharmaceutical industries. Besides, higher total carbohydrates values, and lower protein and ash contents were obtained.

Table 1. Physicochemical analysis of pitahaya cladodes at different maturity stages.

	Tender cladode	Mature cladode
Moisture (%)	89.00 ± 2.00^a	83.00 ± 3.00^b
Ash (%)	0.07 ± 0.01^a	0.09 ± 0.01^a
Total carbohydrate (%)[1]	60.29 ± 5.18^a	75.72 ± 2.98^b
Crude fiber (%)[1]	36.0±3.44^a	21.49 ± 2.69^b
Protein (%)[1]	4.55 ± 1.22^a	2.79 ± 0.37^b
Ether fraction (%)[1]	1.96 ± 0.04^a	1.86 ± 0.01^a
pH	4.67 ± 0.04^a	4.80 ± 0.04^a
Acidity (%)	0.37 ± 0.02^a	0.41 ± 0.02^a
°Bx	3.00 ± 0.00^a	2.80 ± 0.00^a
Density (g/mL)	0.97 ± 0.00^a	0.98 ± 0.01^a
Color L*	51.00 ± 4.50^a	49.6 ± 5.00^a
a*	-18.10 ± 1.40^a	-16.80 ± 2.20^a
b*	29.50 ± 3.80^a	29.10 ± 4.10^a

[1] Percentage values are expressed on a dry basis. Values in the same row that do not share the same letter are statistically different ($n = 3$, $p < 0.05$).

Regarding the factors that affect the chemical composition of nopal cladodes, it is well known is modified by maturity stage, harvest season, environmental and cultivation conditions, post-harvest treatment and type of species (Contreras-Padilla *et al*., 2011; Astello-García *et al*., 2015). An accumulation of total carbohydrates and an increase in titratable acidity have been observed due to crassulacean acid metabolism (CAM) (Martins *et al*., 2023). Mature nopal cladodes are generally reported to contain more total carbohydrates. There is a significant increase in insoluble fiber due to the formation of support tissues. Contreras-Padilla *et al*. (2012) reported that insoluble fiber can increase by up to 200 % after 150 days of growth, while Beyá-Marshall *et al*. (2022) noted an additional 10 % increase at 365 days compared to younger stages. This pattern is commonly associated with the larger size of older cladodes and their contribution to overall crop yield also (Valdez-Cepeda *et al*., 2014). In TC, there is a higher content of free water, more turgid cell walls, and possibly greater porosity. Meanwhile, in MC there is a higher proportion of solids, more mucilage and structural polysaccharides, and greater moisture retention in the later stages of drying due to water retention bound to the tissues (Medina – Torres *et al,* 2008). Even, shifts in the fiber profile have been reported, including different behaviour of soluble and insoluble contents (Contreras-Padilla *et al*., 2012). Similar to this could be in the pitahaya cladodes considering previously rheological study (García-Cruz *et al*., 2013). Meanwhile, the higher protein in TC is typical of actively growing tissues. However, different behaviors were shown by four variants of *Opuntia megacantha* Haw. Cladodes. Juice from mature cladodes presented a higher amount of crude fiber and nitrogen-free extract, whereas juice from tender cladodes contained higher amounts of protein, ether extract, and ash (Pascoe-Ortiz *et al*., 2020).

Regarding the experiences about nopal cladodes in other geographical zones: Beyá-Marshall *et al*. (2022) studied the powders on cladodes (from Litueche, Libertador General Bernardo O'Higgins Region, Chile) of different stages of development (30, 60, 90, and 365 days of regrowth) processed at 40 and 60 °C. The soluble fiber (SF) content does not changed significantly independent of the cladodes age and the drying temperature used. However, insoluble fiber (IF) increased. Until 90 days old IF/SF ratio does not changed, but during the next month's IF proportion increased as the pads lignification processes begin. Furthermore, a differential distribution of the chemical composition of *O. ficus-indica* cladodes sourced from three distinct regions in Morocco was carried out (Razzak *et al*., 2024). It was confirmed by nutritional, mineral and functional characterization of cladodes According to the results, moisture content differs significantly, from 88.21 ± 0.20 % to 92.11 ± 0.10 %, while crude fibers from 20.5 ± 1.9 % to 21.0 ± 0.2 %, protein from 7.54 ± 0.03 % to 9.07 ± 0.16 % and fat content

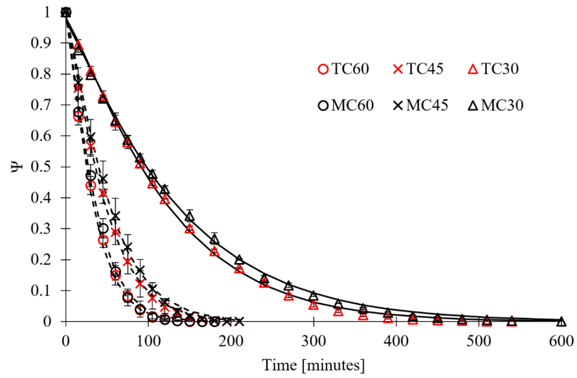

Fig. 1 Convective drying kinetics of *S undatus* cladodes at different air temperatures (60, 45, 30 °C) and maturity stages (MC: mature cladodes, TC: tender cladodes). The discontinuous line represents the simulation using Page model for drying at 60 and 45 °C and Midilli model for 30 °C. Error bars in figure represent ± standard deviation (n = 3).

from 2.30 ± 0.21 to 2.62 ± 0.09 %. Carbohydrate content ranging from 55.40 ± 0.08 % to 55.90 ± 0.60 %.

3.2 Drying kinetics

Figure 1 illustrates the convective drying kinetics of tender (TC) and mature (MC) cladodes as a function of air temperature and physiological stage. The time profiles for reaching equilibrium moisture content for TC were 150, 195, and 540 min at 60, 45, and 30 °C, respectively. Under identical isothermal conditions, MC required 165, 210, and 600 min. These results demonstrate that the drying rate is predominantly governed by the air temperature. The significant reduction in processing time at elevated temperatures is attributed to a greater vapor pressure gradient between the material and the medium interface, which accelerates internal moisture mobility and improves overall mass transfer. However, it is important to note that while excessive temperatures accelerate the process, they may compromise thermosensitive compounds within the cladodes, such as phenolics and mucilage. This finding is consistent with Krokida *et al*. (2003) for nopal (*Opuntia ficus-indica* (L.) Mill) cladodes. A trend toward shorter drying times in TC was identified. However, no statistically significant effect of the maturity stage on the drying kinetics was observed. The following sections present the modeling of moisture kinetics at different drying and maturity temperatures of pitahaya cladodes.

3.3 Water vapor mass transfer modeling by semi-empirical modeling

Drying predominantly occurs within the falling rate period, indicating that internal water diffusion toward the surface is the governing mass transfer mechanism

Table 2. Constants for the nonlinear models for different drying temperature and cladode maturity.

Model	Constant	Tender cladode			Mature cladode		
		30 °C	45 °C	60 °C	30 °C	45 °C	60 °C
Lewis	k	0.0080	0.0214	0.0309	0.0075	0.0193	0.0286
Page	k	0.0039	0.0105	0.0151	0.0051	0.0089	0.0135
	n	1.1474	1.1750	1.1929	1.0795	1.1857	1.1970
Henderson and Pabis	k	0.0083	0.0219	0.0315	0.0076	0.0198	0.0292
	a	1.0346	1.0298	1.0233	1.0114	1.0318	1.0242
Logarithmic	k	0.0033	0.0098	0.0147	0.0039	0.0079	0.0127
	n	1.1791	1.1891	1.1991	1.1264	1.2102	1.2099
	a	0.9822	0.9906	0.9954	0.9720	0.9846	0.9911
	b	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Midilli	k	0.0033	0.0095	0.0151	0.0038	0.0079	0.0127
	n	1.1792	1.1972	1.1907	1.1274	1.2102	1.2097
	a	0.9821	0.9915	0.9956	0.9716	0.9846	0.9909
	b	8.8×10^{-8}	0.0000	0.0000	8.8×10^{-8}	0.0000	0.0000
Two-term	a	1.0346	1.0298	1.0233	1.0114	1.0318	1.0242
	b	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	k_0	0.0083	0.0219	0.0315	0.0076	0.0198	0.0292
	k_1	0.0536	0.0536	0.0536	0.0536	0.0536	0.0536

(Asrate & Ali, 2025; Lahsasni *et al*., 2004). Water vapor mass transfer was modeled using semi-empirical models (equations 9 - 14). Statistical parameters (R^2, χ^2, and RMSE simultaneously) were used to select the appropriate semi-empirical model and avoid selection bias. R^2 explains the variance, χ^2 penalizes overparameterization, and RMSE measures the absolute physical deviation of the predictions (Luna-Flores *et al*., 2026). Table 2 shows the constants for semi-empirical drying modeling at different drying temperatures and pitahaya cladode maturity.

In the models the constant k mathematically defines the rate of moisture removal during drying. As can be seen k increased progressively with temperature in both young and mature cladodes, demonstrating that higher thermal energy directly decreases the internal resistance to mass transfer. The dimensionless exponent (n), present in both the Page and Midilli models, reflects the deviation from ideal diffusion. When $n \neq 1$, it indicates that the diffusion process is strongly coupled with macroscopic structural changes, such as cell shrinkage and the formation of a surface crust. It is characteristic of mucilage-rich matrices exposed to high temperatures (45 and 60 °C). The specific parameters of the Midilli model (a and b) compensate for drying phenomena in the final stage. In particular, the linear parameter b represents the slow and constant evaporation in the final asymptotic region of the drying curve, allowing the model to successfully predict prolonged drying equilibrium at 30 °C (Erbay & Icier, 2010).

According to the statistical parameters for the nonlinear models (Table 3), the model of Page presents the best fit with experimental moisture ratio for temperatures of 60 and 45 °C, for both mature stages evaluated. On the other hand, for 30 °C the best model was Midilli. The latter was determined considering the lowest *AIC* and *BIC* parameters. In literature, the Page and Midilli models are the most frequently applied equations to describe this behavior in cacti. According to Lahsasni *et al*. (2004), the Page model proved to be the most accurate for describing the solar thin-layer drying of nopal cladodes, achieving correlation coefficients (R^2) exceeding 0.999. The Page model represents a modification of the Lewis model by incorporating an empirical parameter n. Meanwhile, the Lewis model assumes that mass transfer resistance is purely external. The n parameter in the Page model corrects deficiencies in describing the internal resistance to mass transfer within complex matrices (Erbay & Icier, 2010; Kidane *et al*., 2025). Conversely, the Midilli model provided the best fit for the convective drying of thin slices (4 mm) of nopal cladodes. Its empirical constants effectively accounted for the combined effects of air temperature and velocity (Díaz-Ayala *et al*., 2015).

Unlike theoretical models based strictly on Fick's second law, semi-empirical models such as Page and Midilli are grounded in experimental data. The first requires extensive knowledge of the product's physical properties and relies on numerous assumptions that often introduce significant errors. Meanwhile, semi-empirical models are highly practical and precise tools for the design and optimization of industrial cacti dryers. These models enable the prediction of drying times across a range of operating conditions without the mathematical complexity associated with distributed mass transfer equations.

Table 3. Statistical parameters for the nonlinear models for different drying temperature and cladode maturity.

Model	Tender cladode					Mature cladode				
	R^2	RMSE	χ^2	AIC	BIC	R^2	RMSE	χ^2	AIC	BIC
30 °C										
Lewis	0.994	0.025	0.001	-505.062	-502.828	0.996	0.019	0.000	-589.228	-586.911
Page	0.998	0.013	0.000	-595.665	-591.196	0.998	0.015	0.000	-624.267	-619.632
Henderson and Pabis	0.995	0.023	0.001	-518.550	-514.082	0.996	0.019	0.000	-590.008	-585.373
Logarithmic	0.999	0.012	0.000	-600.395	-591.459	0.998	0.014	0.000	-636.167	-626.897
Midilli	0.999	0.012	0.000	-600.395	-591.459	0.998	0.014	0.000	-636.162	-626.892
Two-term	0.995	0.023	0.001	-512.550	-501.380	0.996	0.019	0.000	-584.008	-572.420
45 °C										
Lewis	0.989	0.032	0.001	-306.469	-304.662	0.984	0.039	0.002	-289.839	-288.032
Page	0.994	0.024	0.001	-333.042	-329.429	0.990	0.030	0.001	-311.092	-307.479
Henderson and Pabis	0.990	0.031	0.001	-308.208	-304.595	0.985	0.038	0.001	-290.924	-287.310
Logarithmic	0.994	0.024	0.001	-329.540	-322.313	0.991	0.030	0.001	-307.927	-300.700
Midilli	0.994	0.024	0.001	-329.443	-322.216	0.991	0.030	0.001	-307.927	-300.700
Two-term	0.990	0.031	0.001	-302.208	-293.175	0.985	0.038	0.002	-284.924	-275.890
60 °C										
Lewis	0.990	0.030	0.001	-270.568	-268.904	0.989	0.032	0.001	-265.738	-264.074
Page	0.995	0.022	0.001	-294.367	-291.040	0.994	0.023	0.001	-290.232	-286.905
Henderson and Pabis	0.991	0.030	0.001	-270.783	-267.456	0.990	0.031	0.001	-265.910	-262.582
Logarithmic	0.995	0.022	0.001	-290.502	-283.848	0.994	0.023	0.001	-286.689	-280.034
Midilli	0.995	0.022	0.001	-290.403	-283.749	0.994	0.023	0.001	-286.688	-280.034
Two-term	0.991	0.030	0.001	-264.783	-256.465	0.990	0.031	0.001	-259.910	-251.592

RMSE: Root means square error. AIC: Akaike Information Criterion. BIC: Bayesian Information Criterion.

Table 4. Confidence interval of the effective diffusivity during cladodes drying.

	Confidence interval of the effective diffusivity ($D \times 10^8$) [m^2/s]		
Tender cladode/ Temperature (°C)	Lower limit	Estimate	Upper limit
30	1.778	1.782	1.786
45	5.081	5.199	5.317
60	6.835	6.952	7.068
Mature cladode/ Temperature (°C)	Lower limit	Estimate	Upper limit
30	1.636	1.641	1.646
45	4.317	4.374	4.431
60	6.812	6.986	7.160

3.4 Estimation of effective diffusivity coefficients

Since the cladodes were cut transversely, water transfer predominantly occurs in this direction, as the cuticle is impermeable (Espinosa-Solares & Domínguez-Puerto, 2023). This observation validates the application of the simplified analytical solution of Fick's second law for infinite slab geometry under the evaluated experimental conditions. The effective moisture diffusivity (D) is a parameter that represents the overall rate of moisture migration through the internal capillaries and macromolecular barriers of the food matrix (Medina-Torres, L. 2008).

From a process engineering perspective, the obtained diffusivity values are particularly relevant for dryer design, scale-up, and optimization. Reliable estimates of D enable the prediction of drying times under different operating conditions. Furthermore, it supports the selection of appropriate temperature ranges that balance energy efficiency with product quality preservation. D values obtained for pitahaya cladodes ranged from approximately 1.6 $\times 10^{-8}$ to 7.1 $\times 10^{-8}$ m^2/s, depending on drying temperature and maturity stage (Table 4). These magnitudes fall within the typical range reported for plant matrices with high moisture content and fibrous structure, such as cactus cladodes, leafy vegetables, and other succulent tissues. It confirms the physical consistency of the estimated parameters (Erbay *et al.*, 2010). Figure 2 presents the variation of the natural logarithm of the moisture ratio

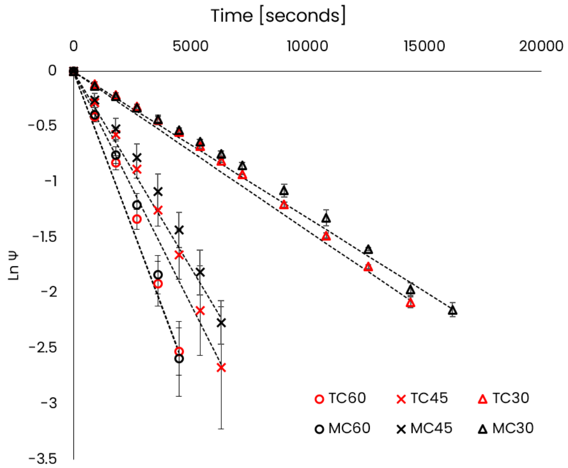

Fig. 2 Natural logarithm of ψ as a function of time at drying temperatures of 60, 45, and 30 °C. Error bars in the figure indicate ± standard deviation (n = 3). The semicontinuous line depicts the simulation results obtained using linear regression (m).

(Ln ψ) as a function of drying time for three operating temperatures. As expected, an increase in drying air temperature increases effective diffusivity for both TC and MC. This behavior reflects the temperature dependence of water molecular mobility within the solid matrix, as higher thermal energy reduces the viscosity of intracellular fluids.

A comparison between maturity stages shows that TC consistently exhibited slightly higher diffusivity values than MC at equivalent drying temperatures, as exception at 60 °C (Table 4). This phenomenon can be attributed to the structural modifications during maturation, specifically the increment of lignification and fiber content (as shown in Section 3.1). TC are characterized by a higher proportion of parenchymatous tissue, greater cellular permeability, and a higher content of soluble polysaccharides and mucilage, which facilitate water mobility. In contrast, MC undergoes progressive lignification and accumulation of insoluble fiber and mineral matter, leading to a denser matrix that imposes greater resistance to internal moisture diffusion.

These differences are consistent with the physiological and compositional changes that occur during maturation. As cladodes develop, soluble fiber gradually decreases, whereas insoluble fiber and ash contents increase, altering both tissue structure and its interaction with the drying process (Contreras-Padilla *et al.*, 2012). Mature cladodes (>40 cm) accumulate greater carbohydrate reserves and structural biomass than younger tissues (Rodrigues *et al.*, 2021). Cladode morphology further influences moisture transport because the waxy cuticle constitutes a nearly impermeable barrier, restricting water migration primarily to the lateral edges of the tissue. During the early stages of *S. undatus* development (approximately 30–50 days after regrowth), cladodes exhibit high

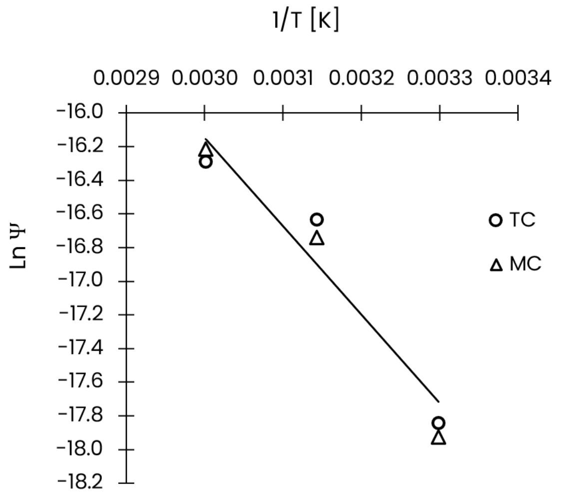

Fig. 3 Logarithms of moisture diffusivity with inverse of temperature (1/T) for tender (TC) and mature (MC) cladodes.

metabolic activity, elevated moisture content, and relatively permeable tissues. As maturation progresses (90–150 days or longer), lignification intensifies and structural carbohydrates and minerals accumulate, reducing tissue permeability and consequently limiting internal moisture diffusion (Da Silva Santos *et al.*, 2026). These structural and compositional changes provide a mechanistic explanation for the slightly lower D values observed in mature cladodes.

Therefore, maturity slows drying mainly due to lignification and changes in the soluble/insoluble fiber ratio (Beyá-Marshall *et al.*, 2022; Contreras-Padilla *et al.*, 2012). At 60 °C, no difference in diffusivity values is observed between mature and young cladodes. It suggests that at that temperature, moisture transport driven by diffusion is greater than the internal resistance to mass transfer by the hydrophilic polysaccharide's characteristic of cactus tissues.

Activation energy (Ea) represents the minimum energy required for water molecules to overcome intermolecular interactions with active matrix sites and initiate diffusion through cell capillaries (Espinosa-Solares and Domínguez-Puerto, 2023). In this study, Ea values were 40.75 and 38.42 kJ/mol for MC and TC, respectively (Figure 3). This difference reflects structural variations in the plant matrix. In MC, the more lignified cell wall creates a physical barrier, requiring more energy to propel water molecules from the tissue core to the surface. With respect to other authors, which reports 45.39 kJ/mol for cladodes of *O. ficus-indica* during infrared drying (Touil *et al.*, 2014). 31.68 kJ/mol for *Austrocylindropuntia cylindrica* Backeb. and 31.44 kJ/mol for *O. ficus-indica* dried in the convection oven (Medina-Torres *et al.*, 2011). This suggests that moisture removal in *S. undatus* requires less energy compared to other cacti like *Opuntia* ssp., which is for the structural

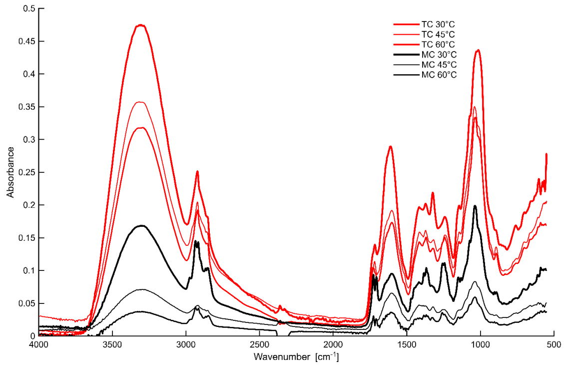

Fig. 4. FTIR spectra of tender cladode flour (TCF) (red lines) and mature cladode flour (MCF) (black lines) dried at temperatures of 30, 45, and 60 °C.

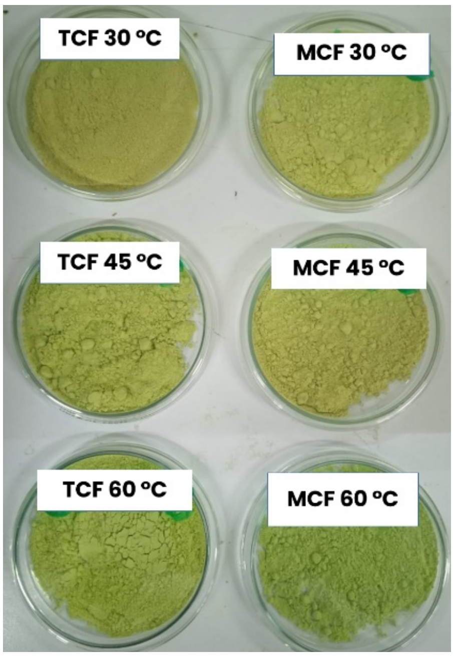

Fig. 5 Color of the powders obtained from tender (TCF) and mature (MCF) cladodes dried at temperatures of 30, 45, and 60 °C.

and characteristic of samples (slices of cladodes).

3.5 *Structural characterization of cladode flours by FT-IR*

FT-IR spectroscopy is one of the most widely used methods for vegetal matrixes characterization, detecting conformational and structural changes provoked by different treatments. In figure 5, the FT-IR spectra for the tender cladode flours (TCF) and mature cladode flours (MCF) samples processed at 30, 45 and 60 °C are exhibited. Less intense signals were observed for the MCF samples compared to those of TCF. Guardiola de León (2018) observed similar behavior in nopal mucilage when the mucilage from the cladodes of five nopal varieties at three different stages of maturity (1, 6, and 12 months) were studied. The signals recorded at 3300 cm^{-1} for all flours are attributed to the -OH group, present in the pyranose ring structure of sugars, or to carboxylic groups, which are abundant in the hydrophilic macromolecules found in all these cacti.

Similarly, significant changes were detected in the bands recorded between 2950 and 2900 cm^{-1} depending on the maturity of the cladodes and the temperature. These signals correspond to the stretching of the C-H bond in the -CH, -CH_2, and -CH_3 groups. Differences in the crude fiber content of the two cladodes could explain this behavior. The TC variety had higher content of crude fiber and protein.

The following significant bands were detected in the fingerprint region between 2000 and 1000 cm^{-1}. Between 1750 and 1700 cm^{-1}, a doublet signal was observed, which could correspond to the stretching vibration of the carbonyl C=O bond. This vibration is present in the acetyl and uronic ester groups found in polysaccharides such as pectin and hemicellulose. On the other hand, this signal could suggest the presence of organic acids, such as malic acid, previously detected in pitahaya cladodes. The signal at 1594 cm^{-1} corresponds to an elongation in the aromatic ring of lignin (Rondán-Flores *et al.*, 2026). More intense bands were observed at 1600 cm^{-1} in the TCF samples, obtained mainly at 60 °C. According to Guardiola de León (2018), these are related to the tensional vibration of the carboxyl group (-C=C-). This is consistent with the findings on pitahaya peel flour reported by Sánchez-Romero (2020). Furthermore, peaks at 1300 and 1200 cm^{-1} could be assigned to the bending vibration of the C-O-C bridge tension observed in carboxylic acids. Meanwhile, band observed at 1050 cm^{-1} indicates the presence of furanose and α- and β-pyranose rings. Previously, signals at 1300, 1245 and 1033 cm^{-1} were observed for pitahaya peel mucilage by Sánchez-Romero (2020), suggesting the presence of galacturonic acid and pectinic nature of the mucilage.

The results demonstrate that differences in intensity of signals were registered for TCF and MCF, depending on the maturity degree and drying temperature conditions. Samples of TCF, exhibited more intensive signals, mainly that processed at 60°C. These facts indicate that behavior will depend of compositional variation of cladodes during maturation process and on possible structural or conformational changes of mucilage molecules at 60°C, favoring detection of chemical groups of macromolecules.

On the other hand, several analytical evidences point to the pectinolytic nature of the pitahaya mucilage. So it can be considered a complex heteropolysaccharide, including not only galacturonic

Table 5. Color analysis of pitahaya cladode flours at different maturity stages.

Temperature (°C)	L*	a*	b*	Hue	Croma
			TCF		
30	76.1 ± 0.5[a]	-8.4 ± 0.0[a]	31.1 ± 0.2[a]	105.13 ± 0.12	32.18 ± 0.25
45	74.8 ± 0.1[a]	-8.7 ± 0.2[a]	29.5 ± 0.1[a]	106.43 ± 0.41	30.76 ± 0.04
60	74.0 ± 0.4[a]	-11.5 ± 0.1[b]	25.6 ± 0.0[b]	114.19 ± 0.19	28.06 ± 0.05
			MCF		
30	72.6 ± 0.3[a]	-5.6 ± 0.4[a]	28.2 ± 0.1[a]	101.23 ± 0.82	28.75 ± 0.02
45	73.5 ± 0.2[a]	-101.1 ± 0.0[b]	28.6 ± 0.2[a]	109.45 ± 0.13	30.33 ± 0.19
60	72.3 ± 0.6[a]	-11.2 ± 0.1[b]	27.4 ± 0.2[a]	112.23 ± 0.33	29.6 ± 0.15

TCF: tender cladode flour; MCF: mature cladode flour. Values represent mean ± standard deviation. Means sharing the same letter in the same column are not significantly different (α:0.05, n: 3).

acid. Other monomers contained in the structural side chains are: L-arabinose, D-galactose, L-rhamnose, and D-xylose (Pascoe-Ortiz *et al.*, 2020; Rondán-Flores *et al.* 2026). The physicochemical properties of the mucilage will depend on the proportion of these monomers in the molecule. Therefore, it varies according to several factors related to the crop, such as: variety, age, environmental conditions, structure used for extraction (fruit, peel, cladode), as well as the mucilage extraction conditions (Contreras-Padilla *et al.*, 2012; Guardiola de León, 2018; Pascoe-Ortiz *et al.*, 2020).

3.6 *Effect of drying temperature and maturity degree on cladodes flours properties*

3.6.1 *Behavior of color attributes*

The color analysis of TCF and MCF, obtained after drying at 30, 45 and 60 °C, was carried out (Figure 4) to investigate the influence of maturity stage and drying temperature on this property. Table 5 shows values of measured a*, b*, L*, and calculated color attributes C* and h*. Regarding the L* and b* values, no significant differences across treatments were observed. Furthermore, the same behavior between TCF and MCF samples was exhibited. In contrast, significant differences ($p \leq 0.05$) across treatments for a* values (redness/greenness) were evidenced. Color of cladodes of cactaceae is due to the presence of chlorophylls (green pigments). Then, the decrease in green (a* less negative or more positive) with temperature suggests chlorophyll degradation. In this sense, gradual heating of green leaves up to non-physiological temperatures often demonstrated thermal sensitivity of chlorophyll, independent of its interactions with plant macromolecules. Previously, Lípova *et al.* (2010) evidenced the heat-induced disassembly and denaturation of chlorophyll- protein complexes. The authors demonstrated that at 40-50°C and around 60°C distinct changes in these molecules were observed, Furthermore, between 70 and 80°C a complete denaturation and degradation of complexes occurred.

On the other hand, the results of fitting the general linear statistical models to relate C* and h*, to the predictive factors (maturity degree and drying temperature) were analyzed. The carried-out ANOVA evidenced that there is a statistically significant relationship ($p \leq 0.05$) between color saturation and the independent variables, with a 95.0 % confidence level. The statistical significance for C* of each factor and their interaction was shown, corresponding to the drying temperature, the highest p-value (0.0001). A similar behavior for h* related with color tone was observed. The statistical significance ($p \leq 0.05$) for this parameter of both predictive factors was demonstrated. However, no statistical significance for their interaction was observed. These results are relevant, as color serves as a primary quality indicator in dehydrated products like flours, directly influencing sensory acceptance, and reflecting the stability of some bioactive compounds.

3.6.2 *Behavior of techno-functional properties*

As shown in Table 6, increasing the drying temperature resulted in a significant decrease ($p \leq 0.05$) in solubility for both types of cladodes. However, no significant differences between TCF and MCF at any given drying temperature were found. Regarding WHC, significant differences between TCF and MCF were observed (Table 6). The WHC values increased as the drying temperature rose was observed. Flours dried at 30 and 45 °C show results comparable to soybean (*Glycine max* (L.) Merr.) flour (142 %), corn husk (*Z. mays*) (317 %), wheat (*T. aestivum*) (291 %), and cabbage (*Brassica oleracea* L.) (318 %). Meanwhile, at 60 °C, the flours reached values similar to nopal flour (575 %), carrot (*Daucus carota* subsp. Sativus (Hoffm.) Schübl. & G. Martens) bagasse (636 %), and beet (*Beta vulgaris* subsp. vulgaris) bagasse (604 %) (Ramírez & Pacheco, 2009). This high WHC values are associated with fiber content and

Table 6. Techno-functional properties of pitahaya cladode flours.

Temperature (°C)	Solubility (%)		WHC (%)	
	TCF	MCF	TCF	MCF
30	92.45 ± 0.25[a]	96.21 ± 0.70[a]	144.41 ± 12.62[b]	160.67 ± 4.71[c]
45	83.10 ± 4.79[b]	87.83 ± 0.61[b]	160.82 ±3.68[e]	279.88 ± 46.84[d]
60	71.58 ± 3.20[c]	79.19 ± 3.32[c]	652.85 ± 10.70[g]	760.00 ± 11.70[f]

TCF: tender cladode flour; MCF: mature cladode flour. Means with different letters in the same column/row are significantly different (α:0.05, n: 3).

the ability of soluble constituents (pectins, mucilages, and soluble hemicelluloses) to bind water within the matrix (Sang *et al*., 2021).

The results of fitting the linear statistical models to relate the solubility and WHC to independent variables were checked. The ANOVA demonstrated that there was a statistically significant relationship ($p \leq 0.05$) between each property and temperature with a 95.0 % confidence level. However, no statistical significance ($p \geq 0.05$) for maturity degree and its interaction with temperature was evidenced. These results align with Díaz-Ayala *et al*. (2015), who demonstrated that the solubility of hydrosoluble compounds, such as mucilage and polysaccharides in nopal cladodes, decreased progressively with temperature. Partial thermal degradation of these functional components has been reported even at 60 °C. Similarly, Vargas-Rodríguez *et al*. (2018) showed the solubility behavior of *O. ficus-indica* mucilage with different solvents, acids, and bases at different temperatures. In water, from 25 to 60°C, solubility decreases considerably. The reduction in solubility indicates a possible thermal partial denaturation of soluble proteins and the formation of insoluble complexes between polysaccharides and minerals, as previously observed in other cacti matrices processed at high temperatures.

On the other hand, according to some authors, the drying method and temperature significantly influence the solubility and hydration properties of vegetable flours. These conditions directly affect food functionality (Martínez-Girón *et al*., 2022). Their relation can vary depending on their plant origin and chemical composition. For instance, convective drying has been shown to result in higher water retention in pineapple peels (Carvalho *et al*., 2025). While in some mucilages, like chia and flax, both properties change proportionally, in others like *Psyllium*, low solubility can still show a great ability to retain water. It has been shown that external factors like pH, temperature, ionic strength, and the presence of hydrophobic groups can affect this relationship. Furthermore, the dependence on the WHC on the structure and composition of the mucilage within the cladodes has been demonstrated in cacti and always is not straightforward. This property depends on hydrophilic polysaccharides and the structure of the water-storage parenchyma. These compounds act as molecular sponges, because their soluble or gelled fractions increase retention capacity and the rate of absorption into aqueous compartments.

In this sense, Méjía-Alcántara (2022) showed that nopal mucilage had lower solubility than mesquite gum, 56.74 ± 0.4 g/g (g of water/g of powder) vs. 84.30 ± 0.53 g/g, respectively. However, it showed a higher WHC value (in g of water/g of powder), 2.46 ± 0.07 g/g compared to the gum (0.56 ± 0.06). Meanwhile, more recently, Coelho and Murowaniecki (2025), in a study on the functional properties of *O. ficus* and *Pilosocereus pachycladus* (facheiro), demonstrated that the latter had a higher WHC (8.56 g/g) than the nopal dispersion at the same concentration (6.12 g/g), even though it showed lower solubility.

Conclusions

Convective drying of pitahaya cladodes demonstrated that both drying temperature and maturity stage significantly affect mass transfer behavior and effective moisture diffusivity. Some compositional differences of cladode flours were evidenced by proximal and FT-IR analysis. Furthermore, different techno-functional properties of the resulting flours were evidenced. The high crude fiber content and water-holding capacity observed support the potential of pitahaya cladode flours, reinforcing the relevance of this byproduct. Higher temperatures accelerated drying and increased water absorption capacity, while solubilities of the flours were reduced, highlighting the need for a balanced selection of processing conditions depending on the intended food application.

This study provides the first systematic report on the combined effect of drying temperature and maturity stage on the techno-functional properties of *S. unda*tus cladode flours, offering a scientific basis for their agro-industrial waste valorization strategies, according the circular bioeconomy principles. The technical characterization presented here provides the foundation for closing the production loops of dragon fruit cultivation, reducing environmental impact by converting pruning waste into value-added resources, thereby supporting the economic and environmental sustainability of producing regions.

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