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Impact of drying temperature and slice thickness on the drying kinetics, color properties, and antioxidant activity of the Egyptian *Opuntia dillenii* fruit

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RESEARCH PAPER

Abstract

This study examined how drying temperature (50°C, 60°C, and 70°C) and slice thickness (0.5 cm and 1.5 cm) influence the drying behavior and quality of *Opuntia dillenii* slices using a hot air dryer. Key parameters, such as color, ascorbic acid (AA), total phenolic content (TPC), and free radical scavenging activity (FRSA), were analyzed. Drying kinetics followed Wang and Singh and Thomson models, showing faster moisture reduction at higher temperatures and in thinner slices. Effective moisture diffusivity ranged from 1.1399×10^{-8} to 5.9273×10^{-8} m^2/s and activation energy from 20.34 kJ/mol to 41.99 kJ/mol. Higher temperatures and thicker slices caused more color changes and nutrient losses, particularly in AA, betalains, TPC, and FRSA. Optimal drying conditions, combining higher temperatures and thinner slices, enhanced drying efficiency while preserving nutritional quality.

Keywords: color; DPPH; hot air drying; *Opuntia dillenii*; total phenolic content

Introduction

Opuntia fruits, also known as prickly pears, are noted for their distinctive appearance, with vibrant hues ranging from deep red to red-purple (Lu *et al.*, 2023). *Opuntia*, a fruit native to the Americas, belongs to the cactus family and thrives globally in arid and semi-arid regions (de Souza *et al.*, 2015). With their unique blend of flavor, nutrition, and medicinal potential, *Opuntia dillenii* fruits continue to captivate both gastronomic enthusiasts and health-conscious consumers globally (de Souza *et al.*, 2015). *Opuntia dillenii* is used in yogurt, snacks, and margarine as a food supplement or to improve the sensorial qualities of food and pharmaceutical products with natural ingredients, which are generally more accepted than synthetic colorants or other additives (Lu *et al.*, 2023). However, *Opuntia dillenii* fruits are highly perishable and have a short shelf life because of their high moisture and nutrient contents, and microbial activity, enzymes, and chemical reactions are the main causes of fruit deterioration (Alshaikhi *et al.*, 2023). Dehydration of plant materials to reduce the moisture content (D_O) is a highly successful approach for prolonging its lifespan, and convective drying is the most employed process for achieving this goal (Pateiro *et al.*, 2022). Drying is a common procedure utilized in fruit preservation, offering a versatile and efficient means of extending the shelf life of fruits while preserving their nutritional value and sensory qualities (Pateiro *et al.*, 2022). By controlling dehydration conditions, drying technologies remove moisture from

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fruits, inhibiting microbial growth and enzymatic activity that prevents spoilage (Sturm *et al.*, 2023). Exposure to hot air during drying processes may negatively impact sensory properties, antioxidants, enzymes, vitamins, and other beneficial components, potentially diminishing the health benefits of dried foods (Demiray *et al.*, 2023; Ghafoor *et al.*, 2020). However, numerous researchers revealed that with careful control of drying conditions, such as temperature, relative humidity, air velocity, and processing time, it is possible to minimize these losses and retain a significant portion of bioactive substances (Doymaz, 2012; Korese *et al.,* 2021). Various studies are in progress to identify optimal drying conditions to achieve a correct balance between preservation and nutrients retention, aiming to provide consumers with dried foods that offer both convenience and nutritional value.

The impact of drying conditions on *Opuntia dillenii* fruits have largely remained unexplored, prompting this study to delve into the effects of drying temperature (DT) and slice thickness (ST) on the bioactive compounds present in these fruits (Demiray *et al.*, 2023). From an engineering standpoint, it is critical to understand in a better manner the *Opuntia dillenii* drying kinetics to design, optimize, and control the drying process. Accurate modeling enables design engineers to select optimal operating conditions. Many mathematical models have been presented to describe the process of drying, and thin-layer drying models have been widely used. The drying kinetics of many fruit and vegetable products have been investigated by many researchers (Darvishi *et al.*, 2014; Falade and Solademi, 2010; Guiné *et al.*, 2014; Wu *et al.*, 2014). Drying kinetics refers to the study of how moisture is removed from materials, such as food products, during drying. It involves understanding the rate of water loss, the influence of factors such as temperature, humidity, and material thickness, and the mathematical models that describe these processes. Properly controlled drying preserves the structural integrity, nutritional content, and bioactive compounds of foods. Additionally, it extends shelf life, reduces microbial activity, and minimizes storage and transportation costs. Therefore, the main purposes of the current research were to: (1) determine the effect of drying temperature (DT) and slice thickness on drying time of *Opuntia dillenii* slices, (2) assess an appropriate drying model, (3) study the drying kinetics and compute effective moisture diffusivity (D_{eff}) and activation energy (E_a) of *Opuntia dillenii* slices, and (4) determine the impact of drying temperature and slice thickness on the quality characteristics of dried *Opuntia dillenii* slices.

Material and Methods

Completely grown *Opuntia dillenii* fruits were acquired from the Faculty of Agriculture, Suez Canal University, Ismailia, Egypt, and kept in a refrigerator at 4±1°C until drying and analysis. 2,2-Diphenyl-1-pricrlhydrazyl (DPPH) and gallic acid (GA) were purchased from Sigma-Aldrich (St. Louis, MO, USA). All other chemicals, reagents, and solvents were of analytical grade.

Drying process

Before drying, *Opuntia dillenii* fruits underwent a thorough washing with running tap water to eliminate dirt and glochids (thorns), followed by the removal of the uncolored sides (top and bottom). Subsequently, the fruits were sliced into two different thicknesses of 0.5 cm and 1.5 cm. Thereafter the slices were placed in a uniform arrangement on a perforated stainless-steel tray, with a weight of roughly 2.25 kg/m^2. The process of drying was achieved using a hot air dryer (F115, WT binder, Germany) at 50°C, 60°C, and 70°C. The relative humidity and air velocity were maintained at 32±1% and 0.6 m/s, respectively. During the drying process, weight loss in samples was checked at every 1 h, and the process was stopped when their weight was stabilized. The drying process was conducted thrice, and the drying curves were constructed using the average moisture ratio (MR) at each time point (Doymaz, 2012). Following the drying process, the product was initially stored at ambient temperature for 30 min in a desiccator. Afterward, it was held for 1 h at a temperature of 4±1°C and frozen at -20°C.

Mathematical modeling

Lahsasni *et al.* (2004) presented the equations utilized to determine the moisture ratio and drying rate at specific time intervals during the drying process,

$$MR = \frac{M - M_e}{M_o + M_e}, \quad (1)$$

where M, M_o, and M_e are the moisture contents at any time, initial moisture content, and equilibrium moisture content, respectively. The drying rate of the samples was calculated using the following equation:

$$\text{Drying rate} = \frac{M_t + dt - M_t}{dt}, \quad (2)$$

where M_t and M_{t+dt} are the moisture content at "t" and moisture content at "$t + dt$" (g moisture/ g dry matter), respectively, (t) is the drying time (min), and (dt) is the time derivative (min).

The drying information collected was applied in five models for thin-layer drying outlined in Table 1 (Li *et al.*, 2019) using nonlinear least squares regression analysis.

Table 1. Mathematical models applied to the *Opuntia dillenii* fruit slices drying curves.

Model name	Model equation
Lewis	MR = exp (–kt)
Page	MR = exp (–kt^n)
Henderson and Pabis	MR = a exp (–kt)
Wang and Singh	MR = 1 + at + bt^2
Thomson	t = a (ln MR) + b (lnMR)^2

MR: moisture ratio.

This analysis was carried out utilizing statistics software (Statistics 6.0, Statsoft Inc., Tulsa, OK, USA). The correlation coefficient (R^2) serves as a crucial parameter in selecting the most suitable model to characterize the drying profiles of dehydrated samples. It serves as a metric to evaluate the precision of the fit and determine the model's efficacy.

Moisture diffusivity and energy consumption

The diffusion equation proposed by Fick was employed to elucidate the dehydration process of food products during the phase of diminishing drying rates. The equation was obtained by Crank (1975) and finds utility across various product categories. To streamline the prolonged drying duration, a more concise representation of this solution is provided in logarithmic notation, as depicted in Equation (3) (Falade and Solademi, 2010):

$$\ln MR = \left(\ln\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}\right)t. \quad (3)$$

The effective moisture diffusivity (D_{eff}) is quantified in square meters per second (m^2/s), while the thickness of the *Opuntia dillenii* is characterized by (L). Determining the diffusivities involves plotting the natural logarithm of the moisture ratio (lnMR) against the drying time (t) in the equation, yielding a linear relationship with a slope of ($\pi^2 D_{eff}/4L^2$).

An Arrhenius-type Equation (4) was employed to examine the correlation between effective diffusivity and temperature. This equation facilitated the calculation of the activation energy (E_a) (Xiao *et al.*, 2010),

$$D_{eff} = D_o \exp\left(\frac{-Ea}{RT}\right). \quad (4)$$

The E_a of moisture diffusion is quantified in kJ/mol, while the diffusivity value for infinite moisture content (D_o) is expressed in m^2/s. The universal gas constant (R) is 8.314 kJ/mol, and the drying air temperature is denoted by (T).

Color measurements

The values of color parameters (L*, a*, and b*) were recorded using a color reader (CR-10, Minolta, Konika Inc., Japan). chroma (C*) and total color difference (ΔE) of *Opuntia dillenii* were calculated using Equations (7) and (8), respectively, as delineated by Vega-Gálvez *et al.* (2012),

$$C = (a^2 + b^2)^{0.5} \quad (7)$$

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (8)$$

L_0^*, a_0^*, and b_0^*, denote fresh color values.

Determination of betalain pigment

Betalain pigment was measured and calculated according to the method delineated by Ravichandran *et al.* (2013). The sample (100 mg) was mixed with 10 mL of ethanol (50%), and the mixture was agitated for 10 s, centrifuged (6,000 rpm/ 10 min), and the supernatant was collected. Absorbance of the supernatant at two wavelengths (538 nm and 480 nm) was recorded using a spectrophotometer and the total betalain concentration was calculated using Equation (6),

$$\text{Total betalain content}\left(\frac{\text{mg}}{100\text{g}}\right) = \frac{\text{A*DF*MW*100}}{\text{e*l}}, \quad (6)$$

where A: absorbance of sample, DF: dilution factor, MW: 550 g/mol and 308 g/mol are the molecular weights of betacyanin and betaxanthins, respectively, e: molar extinction coefficient is 60,000 L/mol for betacyanin and 48,000 L/mol for betaxanthins, and 1 is the cuvette length.

Determination of ascorbic acid (AA)

The AA content of dried *Opuntia dillenii* slices was determined using the 2,6-dichlorophenol indophenol titrimetric method (Association of Official Analytical Chemists [AOAC], 2000). The dried fruit sample (5 g) was crushed with 50 mL of oxalic acid (4%), and the final volume reached 100 mL. The solution was then titrated with a calibrated 2,6-dichlorophenol indophenol solution until it turned pink, ensuring that the color remained stable for at least 15 s. The concentration of AA was quantified as mg/100 g, dry weight [dw].

Total phenolic content (TPC)

Total phenolic content was determined using the method outlined by Chikpah *et al.* (2022), with some

modifications. Briefly, the dried sample (1 g) was mixed with 80% methanol acidified with 0.1% hydrochloric acid (6 mL). The mixture was shaken for 20 min at room temperature and centrifuged at 3,000 rpm for 15 min (ICE PR-7000, Tempe, Arizona, USA). The supernatants were separated and filtered through Whatman filter paper No. 1. After that, 100 µL of supernatant was mixed with 900 µL of Folin–Ciocalteu reagent. Following a duration of 5 min, a volume of 750 µL of sodium carbonate (7.5%, w/v) was introduced into the mixture. After intense agitation for 30 s, the mixture was allowed to settle undisturbed for 1.5 h at room temperature, and the formed blue color was recorded at 725 nm. A calibration curve for GA was created, and the results were recorded as mg of gallic acid equivalent/100 g.

Free radical scavenging activity (FRSA)

The same extract used in the measurement of TPC was used in the determination of Free radical scavenging activity (FRSA) as described by Ravichandran *et al.* (2013). The extract (100 µL) was combined with 3,900 µL of DPPH (0.1 mM). The final mixture was rapidly stirred for 30 s and kept in the dark at room temperature for 30 min. Absorbance was measured at 515 nm using a spectrophotometer. An assessment was also conducted on a control sample that did not contain the extract. Afterward, FRSA (%) was assessed using Equation (5),

$$\text{Free radical scavenging activity } (\%) = \left[\frac{A_{control} - A_{sample}}{A_{control}}\right] x100, \quad (5)$$

where A was absorbance at 515 nm.

Statistical analysis

All assays were performed in triplicate, and the obtained results were presented as means ± stander deviation (SD). The experimental data underwent analysis of variance (ANOVA) using CoStat version 6.303, Co Hort software, USA. The Duncan test was utilized to analyze data, and a level of $p < 0.05$ was used to determine significance between values.

Results and Discussion

Drying characteristics and mathematical modeling

Opuntia dillenii fruit slices were arranged as a single layer with different thicknesses of 0.5 cm and 1.5 cm and at different temperatures of 50°C, 60°C, and 70 °C in a hot oven dryer. The study examined the effects of varying parameters (DT and ST) on changes in moisture content over drying time. Figure 1A illustrates the drying curves of *Opuntia dillenii*, which demonstrate a clear exponential trend, wherein moisture content decreased with increasing DT and decreasing ST. Elevating the DT from 50°C to 60°C reduced the final time needed to achieve equilibrium moisture content from approximately 1,080–1,500 min to approximately 1,020–1,140 min (a reduction of 5.56% to 24% for the thickness of 0.5 cm and 1.5 cm, respectively). Similarly, raising the temperature to 70°C reduced the drying time to approximately 660–840 min, representing a reduction of 38.89% and 44% for the thickness of 0.5 cm and 1.5 cm, respectively, compared to those at 50°C for thickness (0.5–1.5 cm). In this context, it can be asserted that both DT and ST significantly impacted drying time ($p < 0.05$). Likewise, Jeevarathinam *et al.* (2022) observed a notable influence

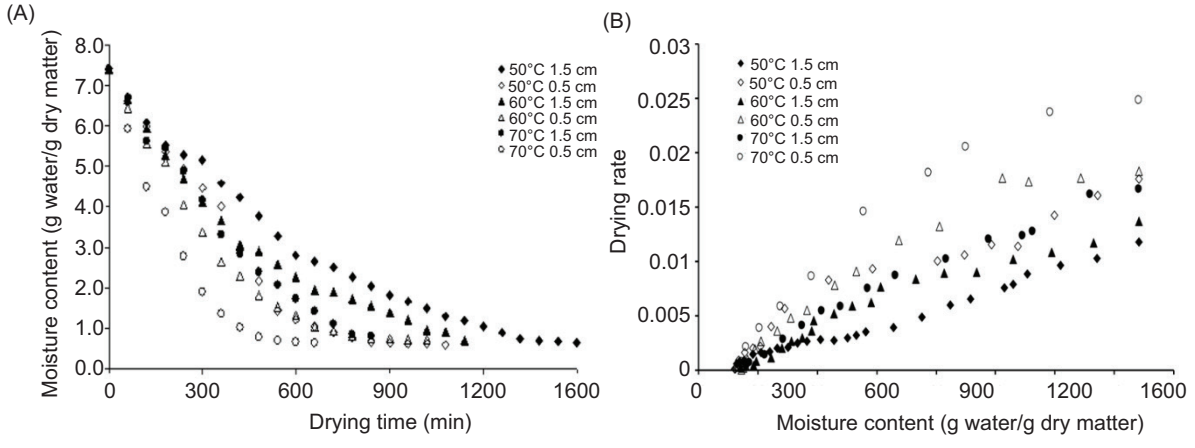

Figure 1. (A) Drying curves for *Opuntia dillenii* fruit slices at different drying temperatures and slice thicknesses; (B) Drying rate curves for *Opuntia dillenii* slices at different drying temperatures and slice thicknesses.

of DT on needed drying time, remaining moisture, and drying speed. Less thickness and higher temperature are expected to reduce drying time. This is because in less thickness, the amount of water accessible for evaporation is lower, and the distance that water needs to reach the surface decreases, resulting in a shorter drying period (Demiray *et al.*, 2023). As temperature rises, the rate of water evaporation accelerates, leading to a shorter drying period (Chikpah *et al.*, 2022). These results are consistent with earlier studies on the drying of different foods, including apple slices and persimmons (Demiray *et al.*, 2023; Doymaz, 2012).

Relationship between the moisture content (on a dry basis) and the rate of moisture removal at various DT and ST is shown in Figure 1B. As moisture content decreases, the drying rate diminishes accordingly. Notably, the drying process does not maintain a consistent rate throughout but predominantly occurs during the falling-rate period. This phase is characterized by internal diffusion processes driven by the presence of bound water. Through the declining drying rate phase, water removal from larger capillaries takes precedence over that from smaller vessels, resulting in a decrease in evaporation rate during the initial half of this phase.

The moisture content data gained at various DT and ST were converted into dimensionless moisture ratios and analyzed subsequently using five thin-layer drying models (Table 1). The mean values (n = 3) of kinetic and empirical parameters for all models are summarized in Table 2. The model exhibiting the highest coefficient (R^2)

Table 2. Values of kinetic and empirical parameters and results of statistical analysis for the modeling of drying curves of *Opuntia dillenii* fruit slices at different air temperatures and thickness.

Model name	Temperature (°C)	Thickness (cm)	Model constants	Coefficient of determination (R^2)
Lewis	50	1.5	k = 0.0025	0.8448
	50	0.5	k = 0.0051	0.8625
	60	1.5	k = 0.0027	0.9511
	60	0.5	k = 0.0051	0.8987
	70	1.5	k = 0.0040	0.7765
	70	0.5	k = 0.0079	0.8970
Page	50	1.5	k = 0.00063, n = 1.1801	0.9614
	50	0.5	k = 0.00013, n = 1.5295	0.9654
	60	1.5	k = 0.00110, n = 1.1290	0.9935
	60	0.5	k = 0.00046, n = 1.3533	0.9823
	70	1.5	k = 0.00049, n = 1.3061	0.9509
	70	0.5	k = 0.00073, n = 1.3772	0.9788
Henderson and Pabis	50	1.5	a = 1.0808, k = 0.0020	0.9870
	50	0.5	a = 2.3594, k = 0.0061	0.9217
	60	1.5	a = 1.0784, k = 0.0026	0.9940
	60	0.5	a = 2.0546, k = 0.0072	0.9384
	70	1.5	a = 1.7044, k = 0.0050	0.8217
	70	0.5	a = 1.9613, k = 0.0095	0.9340
Wang and Singh	50	1.5	a = –0.0013, b = 5E – 07	0.9953
	50	0.5	a = –0.0020, b = 1E – 06	0.9831
	60	1.5	a = –0.0018, b = 9E – 07	0.9942
	60	0.5	a = –0.0029, b = 1E – 06	0.9973
	70	1.5	a = –0.0020, b = 9E – 07	0.9950
	70	0.5	a = –0.0037, b = 3E – 06	0.9976
Thomson	50	1.5	a = –636.84, b = -72.286	0.9949
	50	0.5	a = –326.09, b = -27.854	0.9490
	60	1.5	a = –500.74, b = -54.098	0.9949
	60	0.5	a = –305.53, b = -25.579	0.9890
	70	1.5	a = –408.71, b = -51.373	0.9870
	70	0.5	a = –199.72, b = -17.273	0.9867

was identified as the most appropriate model for elucidating the drying behavior of *Opuntia dillenii*. Among the drying models assessed, the Wang and Singh model yielded the highest R^2 value, closely followed by the Thomson model (considering temperature and thickness). Hence, these models appear to depict accurately the drying characteristics of *Opuntia dillenii*.

Moisture diffusivity and activation energy

Table 3 presents the effective moisture diffusivity (D_{eff}) values of air-drying *Opuntia dillenii* slices at various air temperatures and thicknesses. The average D_{eff} values of *Opuntia dillenii* slices ranged from 1.1399×10^{-8} m^2/s to 5.9273×10^{-8} m^2/s. As expected, the D_{eff} demonstrated a noticeable increase with higher drying temperatures. The average D_{eff} values observed in our study were within the range of biological materials, which was between 10^{-8} m^2/s and 10^{-12} m^2/s (Zogzas *et al.* 1996). Specifically, the D_{eff} values for *Opuntia dillenii* slices with a thickness of 0.5 cm increased from 1.5452×10^{-8} m^2/s at 50°C to 2.4064×10^{-8} m^2/s at 70°C. Comparable trends in D_{eff} values were observed in previous studies on the convective drying of Monukka seedless grapes (Xiao *et al.*, 2010) and pumpkin (Chikpah *et al.*, 2022). Xiao *et al.* (2010) observed that elevating the drying temperature enhances the energy and mobility of water molecules, thereby augmenting the rate of moisture diffusion.

The Arrhenius plot's gradient, $\ln D_{eff}$ versus the reciprocal of absolute temperature, serves to determine E_a. Our findings revealed a direct correlation consistent with the Arrhenius-type relationship, evidenced by R^2 values of 0.9343 and 0.9741 for 1.5 cm and 0.5 cm, respectively. Slope of the line, calculated as the negative of E_a divided by the gas constant (-Ea/R), coupled with its intercept, represents the natural logarithm of pre-exponential factor, $\ln D_o$. The respective diffusion values were determined as 26.48×10^{-2} and 29.53×10^{-6} m^2/s. For the thicknesses of 1.5 cm and 0.5 cm, the E_a for diffusion was measured as 41.99 kJ/mol and 20.34 kJ/mol, respectively. These values closely aligned with those reported for other fruits, such as apples (Meisami-asl *et al.*, 2010) and cape gooseberry (Youssef, 2015).

Color parameters

Color serves as a crucial quality indicator influencing consumers' perception of powdered products, with color assessment being a primary factor in product evaluation (Demiray *et al.*, 2023; Parveez Zia and Alibas, 2021). Therefore, it is imperative for reconstituted powders to resemble closely to the color of fresh products. Table 4 presents L*, a*, b*, chroma (C*), and total color difference (ΔE) of fresh and dried *Opuntia dilleniifruit* slices. The impact of DT and ST on the color of *Opuntia dillenii* was evident, exhibiting a statistically significant effect ($p < 0.05$). Notably, L* values for all dried *Opuntia dillenii* increased significantly across different DT and ST values, compared to the fresh counterparts. This rise in L* values could be due to the effects of drying process on betalain pigment fractions (betaxanthin and betacyanin). It has been reported that high temperature has lower degradation of yellow–red betalain (betaxanthin), compared to red–violet betalain (betacyanin). This phenomenon may cause a partial vanish of dark blue–purple color, consequently the appearance of gloss of betacyanin (Gokhale and Lele, 2014). As both DT and ST increased, the values of a* and b* decreased notably, indicating the sensitivity of betalain pigment to heat (Janiszewska-Turak *et al.*, 2021). This phenomenon suggests that as the drying temperature rises, the breakdown of betacyanin occurs, leading to color transformation in *Opuntia dilleniid* from purple to a more yellowish hue. The increase in yellow betaxanthin characteristics are attributed to either thermochemical transition of betacyanin to betaxanthin or the enhanced extractability of betaxanthin at higher DT (Gokhale and Lele, 2014).

Chroma (C*) values of dried *Opuntia dillenii* slices ranged from 14.34 to 19.23, which were lower than the C* values of fresh sample (22.94). It's noteworthy that

Table 3. Effective moisture diffusivity (D_{eff}) obtained for *Opuntia dillenii* fruit slices at different drying air temperatures and thicknesses.

Temperature (°C)	Thickness (cm)	Effective moisture diffusivity (m^2/s)	Coefficient of determination (R^2)
50	1.5	4.5595×10^{-8}	0.9870
50	0.5	1.5452×10^{-8}	0.9217
60	1.5	5.9273×10^{-8}	0.9940
60	0.5	1.8238×10^{-8}	0.9384
70	1.5	1.1399×10^{-8}	0.8217
70	0.5	2.4064×10^{-8}	0.9340

Table 4. Effect of dehydration process on the color of *Opuntia dillenii* fruit slices.

Color attribute	Drying air temperature (ºC)	Thickness		Mean
		0.5 cm	1.5 cm	
	Fresh sample	31.22 ± 0.25		
L*	50	38.25	39.5	38.88 ± 0.11[a]
	60	38.85	40.1	39.48 ± 0.08[a]
	70	39.15	40.3	39.73 ± 0.70[a]
	Mean	38.75[b]	39.97[a]	
	Fresh sample	20.36 ± 0.37		
a*	50	14.40	14.25	14.33 ± 0.11[c]
	60	16.45	16.25	16.35 ± 0.12[b]
	70	18.95	18.65	18.80 ±0.17[a]
	Mean	16.60 ± 0.27[a]	16.38 ± 0.21[a]	
	Fresh sample	–10.12 ± 0.11		
b*	50	–3.25	–2.00	–2.63 ± 0.14[a]
	60	–2.35	–1.60	–1.98 ± 0.15[b]
	70	–2.10	–1.10	–1.60 ± 0.22[b]
	Mean	–2.57 ± 0.11[a]	–1.57 ± 0.2[b]	
	Fresh sample	22.94 ± 1.30		
Chroma (C*)	50	14.59	14.34	14.47 ± 0.11[c]
	60	16.69	16.58	16.64 ± 0.14[b]
	70	19.23	18.36	18.80 ± 0.21[a]
	Mean	16.84 ± 15[a]	16.42 ± 0.07[a]	
	Fresh sample		0	
Δ*E*	50	12.51	12.94	12.73 ± 0.18[a]
	60	12.02	12.89	12.46 ± 0.22[a,b]
	70	11.20	12.44	11.82 ± 0.25[b]
	Mean	11.91 ± 0.14[b]	12.75 ± 0.18[a]	

Mean values with different superscripts ([a, b, and c]) for the same parameter row (effect of thickness) or column (effect of temperature) are significantly different ($p \leq 0.05$).

temperature has a more pronounced effect on color intensity than thickness. Specifically, C* increased significantly with rising temperature, while differences in thickness did not impact C* values notably. The study also observed that the highest Δ*E* value occurred at 50°C and 1.5 cm. This heightened color change could be attributed to the prolonged exposure to air during the extended drying period. This drying period affects heat-sensitive components and enhances nonenzymatic reactions, degradation of betalain pigments, and oxidation reactions (Jéssica *et al.*, 2013). Our results are in agreement with previous studies, such as Demiray *et al.* (2023), who examined the effects of different temperatures (45°C, 55°C, and 65°C) and sample thicknesses (1.5 mm and 5 mm) on apple slices' color parameters, observing a general decrease in color values with increasing temperature. Thinner samples (5 mm) exhibited lower brightness (L^*) but higher redness (a*) and yellowness (b*), compared to thicker samples. Similarly, Korese and Achaglinkame (2024) reported comparable findings in a study on *Gardenia erubescens*, where slice thickness (3 mm and 5 mm) and drying air temperatures (40–70°C) influenced color parameters. L* significantly increased with both thickness and temperature, primarily due to shorter drying period, which reduced changes in brightness. In contrast, a* and b* values did not decrease significantly with thickness but increased dramatically with higher drying temperatures, probably because of shorter drying period and reduced browning. In summary, the color quality of dried *Opuntia dillenii* slices was directly proportional to the pace of drying. The faster the drying process, the more closely the final product resembled the fresh one, and the fewer undesired color changes occurred. The validity of our explanation was supported by the fact that

0.5-cm-thick *Opuntia dillenii* slices subjected to drying at 70°C exhibited a higher color intensity and a slower rate of color change.

Effect of drying temperature and slice thickness on betalain content, ascorbic acid, total phenolic content, and free radicle scavenging activity

Table 5 illustrates the impact of dehydration on the levels of specific nutrients in *Opuntia dillenii*, including AA, betalain pigment, TPC, and FRSA. As shown in Table 5, the dried *Opuntia dillenii* fruit slice samples displayed lower total betalain content (249.02–304.55 mg/100 g, dw), compared to the fresh samples (682.82 mg/100 g dw). Notably, the overall betalain concentration exhibited a significant decrease with increasing DT. Specifically, samples dried at 50°C contained substantially higher betalain concentration, compared to those dried at 60°C and 70°C. Consistent with this, a study conducted by Ghafoor *et al.* (2020) found that the breakdown proportion of betalain increased with elevated temperatures. This trend aligned with the findings of a previous study (Gokhale and Lele, 2014), where the authors observed a similar reduction in betalain pigment content in *Beta vulgaris* with higher DT. Regarding the influence of ST on total betalain content, samples dried with a thickness of 0.5 cm demonstrated notably higher concentrations, compared to those dried with a thickness of 1.5 cm. This suggested that a longer drying period adversely affected the betalain content.

Notably, the dried samples consistently exhibited lower levels of AA, compared to the fresh ones, with a measured content of 434.62 mg/100 g dw. This reduction in AA content during the drying process was due to both thermal and oxidative degradation of AA (Chikpah *et al.*, 2022; Parveez Zia and Alibas, 2021). Furthermore, the AA content in dried *Opuntia dillenii* decreased significantly with higher DT and ST values. Specifically, the samples dried at 70°C experienced greater loss of AA, compared to those dried at 50°C and 60°C, as indicated in Table 5. Additionally, 1.5-cm thick slices f exhibited notably lower concentration of AA, compared to those with a thickness of 0.5 cm. These findings aligned with previous studies conducted by Korese *et al.* (2021) and Vega-Gálvez *et al.* (2012), which reported a higher sensitivity of AA to heat and its propensity to decompose at elevated temperatures. Similar reduction in the AA content was observed in other dried fruits and vegetables, such as hot air-dried pumpkin (Chikpah *et al.*, 2022), papaya (Minuye *et al.,* 2021), and dried palmyra seed sprout fleshy slices (Korese *et al.,* 2021).

Table 5. Effect of dehydration process on the contents of some bioactive compounds (mg/100 g dw) and FRSA of cactus *Opuntia dillenii* fruit slices.

Parameter	Drying air temperature (ºC)	Thickness		Mean
		0.5 cm	1.5 cm	
Ascorbic acid	50	265.84	245.35	255.60 ± 2.41^{a}
	60	260.13	242.41	251.27 ± 3.54^{a}
	70	231.9	213.17	222.54 ± 2.3^{b}
	Mean	252.62 ± 2. 17^{a}	233.64 ± 1.75^{b}	
Total betalains	50	304.55	284.57	294.56 ± 2.84^{a}
	60	271.62	264.37	267.99 ± 2.41^{b}
	70	256.88	249.02	252.95 ± 1.87^{c}
	Mean	277.68 ± 3.01^{a}	265.99 ± 1.78^{b}	
Total phenolic content	50	437.75	350.56	394.16 ± 2.54^{c}
	60	481.56	444.31	462.94 ± 2.55^{b}
	70	560.72	508.88	534.80 ± 2.74^{a}
	Mean	493.35 ± 1.08^{a}	434.58 ± 2.39^{b}	
FRSA (%, DPPH assay)	50	37.16	35.90	36.53 ± 0.57^{c}
	60	38.79	38.09	38.44 ± 0.21^{b}
	70	39.37	39.02	39.20 ± 0.11^{a}
	Mean	38.44 ± 0.05^{b}	35.67 ± 0.08^{a}	

Mean values with different superscripts ($^{a, b, \text{and } c}$) for the same parameter row (effect of thickness) or column (effect of temperature) are significantly different ($p \leq 0.05$).

The drying procedure had a substantial impact on reducing polyphenol content (Demiray *et al.*, 2023). As shown in Table 5, TPC in dried *Opuntia dillenii* ranged from 350.56 mg/100 g dw to 560.72 mg/100 g dw and was lower than observed in the fresh samples (1052.8 mg/100 g dw). The obtained results aligned with the findings of Parveez Zia and Alibas (2021), who observed a significant reduction in the TPC of dehydrated cornelian cherry. Tan *et al.* (2020) found that polyphenol concentration in dried *Litchi chinensis* decreased during the drying and storage process because of enzymatic oxidation. Decrease in the TPC of dried *Opuntia dillenii* could be attributed to several factors, such as polyphenol interaction with proteins or changes in polyphenol chemical structure that were undetectable or remained unmeasured. These include the breakdown of polyphenol compounds by endogenous enzymes, such as polyphenol oxidase (PPO), and the application of heat during processing (Sturm *et al.*, 2023). Similar results were reported in various food items, including pumpkin slices (Chikpah *et al.*, 2022) and apple slices (Demiray *et al.*, 2023). However, in the case of dried *Opuntia dillenii*, the concentration of TPC increased with reduced ST, and the DT increased from 50°C to 70°C. This phenomenon could be attributed to the rapid deactivation of PPO at higher DT, resulting in the acceleration of moisture removal and the consequent decrease in the enzymatic degradation of polyphenol (Sturm *et al.*, 2023; Vargas-Madriz *et al.*, 2023). Furthermore, elevated DT resulted in the breakdown of plant cell walls, releasing bound phenols and thereby increasing the concentration of TPC (Vargas-Madriz *et al.,* 2023).

The FRSA of fruits and vegetables is largely determined by specific secondary metabolites, such as vitamins, carotenoids, and polyphenols (Ghafoor *et al.*, 2020; Parveez Zia and Alibas, 2021). As depicted in Table 5, dehydration had a notable effect on the antioxidant activity of *Opuntia dillenii*. Across all dried samples, FRSA was reduced, compared to the fresh sample (86.22%). Given that the drying process could negatively impact antioxidant components, this decrease was anticipated. However, there was an enhancement in antioxidant activity with higher drying temperatures. Samples dried at 70°C exhibited greater antioxidant activity than those dried at 50°C. This trend might be linked to the dehydration process that took place at lower temperatures, resulting in prolonged drying periods, which could diminish FRSA (Wanderley *et al.,* 2023). Additionally, the formation and accumulation of melanoidin (Maillard-derived), which possesses varying degrees of FRSA, may enhance the ability to counteract oxidation at elevated temperatures (Shakoor *et al.*, 2022). Throughout the stages of fruit development and dehydration, there is a growing association between FRSA and the overall quantity of TPC (Demiray *et al.*, 2023; Ghafoor *et al.*, 2020).

Conclusion

In this study, drying temperature and slice thickness affected *Opuntia dillenii* fruit slices' drying kinetics and bioactive components. These findings can help produce dried fruits with high antioxidant content and activity. Drying dynamics, color changes, and bioactive composition of dried *Opuntia dillenii* were examined at varying slice thicknesses and convective air-drying temperatures. *Opuntia dillenii* dried well according to the Wang and Singh model. As per the CIELAB (CIE Lab* as per the International Commission on Illumination [CIE]) color standard, L* values increased, while a*, b*, and C* values decreased, compared to fresh samples. As drying temperature and slice thickness increased, a*, b*, and ΔE values decreased less rapidly. TPC and FRSA of dehydrated *Opuntia dillenii* were greatly affected by drying. Thinner (0.5 cm) slices dried faster and preserved more bioactive compounds and antioxidant activity than 1.5-cm thick slices. Despite reduced AA and total betalain, *Opuntia dillenii* slices dried at 70°C preserved best both TPC and FRSA. This suggests that drying *Opuntia dillenii* at 70°C and 0.5-cm thick slices may produce high-quality dried *Opuntia dillenii*. In addition, drying kinetics and color changes may help to anticipate *Opuntia dillenii* drying behavior and quality during convective air drying.

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Author Contributions

All Authors contributed equally to this article.

Conflicts of Interest

We have no conflicts of interest to declare.

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